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Evaluating alternative network configurations and resource allocations for deployed Marine Corps aviation logistics units

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Monterey, California: Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**EVALUATING ALTERNATIVE NETWORK
CONFIGURATIONS AND RESOURCE ALLOCATIONS
FOR DEPLOYED MARINE CORPS
AVIATION LOGISTICS UNITS**

by

Joshua M. Jabin

June 2009

Thesis Advisor:	Moshe Kress
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1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2009	**3. REPORT TYPE AND DATES COVERED** Master's Thesis
4. TITLE AND SUBTITLE Evaluating Alternative Network Configurations and Resource Allocations for Deployed Marine Corps Aviation Logistics Units		**5. FUNDING NUMBERS**
6. AUTHOR(S) Joshua M. Jabin		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Air Systems Command Norfolk, Virginia		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.		
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited		**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS MALSP II, inter-temporal network simulation model, simulation model, Marine Corps aviation logistics, deployed aviation logistics	**15. NUMBER OF PAGES** 85
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

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EVALUATING ALTERNATIVE NETWORK CONFIGURATIONS AND RESOURCE ALLOCATIONS FOR DEPLOYED MARINE CORPS AVIATION LOGISTICS UNITS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This thesis develops a model and performs analysis to estimate the operational effectiveness of the Marine Aviation Logistics Support Program II (MALSP II) under different system configurations and resource allocation policies. MALSP II is designed to protect the aviation logistics system from uncertain, possibly high variance, demand that could have a significant detrimental impact on the material readiness of deployed aircraft. Although an MALSP II pilot program has produced positive results since 2005, the overall design of the logistical support network has not yet been evaluated. We develop an inter-temporal network simulation model that measures the operational effectiveness of the network—with and without an additional level of supply called an Enroute Support Base—using four inventory buffer sizing policies. We use two measures of effectiveness (MOE): PackUp Effectiveness and PartShort. Packup Effectiveness is the current metric used by the Marine Corps to evaluate aviation logistics performance in a deployed setting. It represents the percentage of demands satisfied on the day demanded. PartShort, which is a new MOE proposed in this thesis, represents the magnitude and duration of unsatisfied demands during a certain finite time horizon. For different levels of acceptable risk, we provide recommendations for network configurations and inventory buffer levels. These results can help operational planners improve the efficiency of available resources and maximize the effectiveness of logistical support to deployed bases.

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EXECUTIVE SUMMARY

Marine Corps aviation logistics is in the process of transforming the model used to support deployed operations. For 20 years, the Marine Corps has used the Marine Aviation Logistics Support Program (MALSP)—a planning tool that dictates the necessary people, equipment, spare parts, and mobile containers to deploy in support of contingency operations. MALSP is a "push" system based on periodic fixed-size batches of supply. Due to increased operational requirements in Operation Iraqi Freedom and Operation Enduring Freedom, the Marine Corps has initiated the development of MALSP II, which is designed to protect the logistical system from uncertain, possibly high variance, demand that could have a significant detrimental impact on the material readiness of deployed aircraft. Since 2005, a MALSP II pilot program has produced positive results, but the overall design of the MALSP II logistical support network has not yet been evaluated.

MALSP II is a pull system where supplies are ordered, as needed, following consumption. Inventory buffers at the various nodes of the logistics network are determined by an information tool called the Enterprise Logistics Analysis Tool (ELAT). ELAT gives users four options—no-risk, low-risk, medium-risk and high-risk—to determine inventory buffers that correspond to the 100th, 97th, 94.7^{th} and 87th percentile, respectively, of observed demand distribution during the logistical lead time—called time to reliably replenish (TRR)—specific to the operation supported. In this thesis we evaluate four logistics network configurations and attempt to answer the following questions: (1) at what distance—if at all—does an additional level of supply called an Enroute Support Base (ESB) improve network efficiency and (2) what impact do the four inventory buffer sizing risk levels used by ELAT have on the estimated measures of effectiveness. To answer these questions, we develop an inter-temporal network (ITN) simulation model that measures the operational effectiveness of the network—with and without the ESB—using the four inventory buffer sizing methods used in ELAT.

In the analysis we use two measures of effectiveness (MOE): PackUp Effectiveness and PartShort. Packup Effectiveness is the current metric used by the

Marine Corps to evaluate aviation logistics performance in a deployed setting. It represents the percentage of demands satisfied on the day demanded. PartShort, which is a new MOE proposed in this thesis, represents the magnitude and duration of unsatisfied demands during a certain finite time horizon.

The model compares four network configurations. The first configuration, called ESB0, represents the network without an ESB. The other three configurations, labeled ESB5, ESB3 and ESB1, assume the existence of an ESB and they differ in terms of distance, measured by TRR, from the Parent Marine Aviation Logistics Squadron (PMALS) and the Main Operating Base (MOB): ESB5 is 5 days from the MOBs and 6 days from the PMALS, ESB3 is 3 and 8 days, respectively, and ESB1 is 1 day from the MOBs and 10 days from the PMALS. Each configuration is modeled using each one of the four risk levels—no-risk, low-risk, medium-risk, high-risk—used in ELAT to determine inventory buffers. Each instance of the simulation runs for 360 days and is replicated 20 times. The model produces expected operational effectiveness measured by the two aforementioned MOEs for the varying levels of input determined by the selected risk level. Together, these parameters—inputs and MOEs—are used for determining efficiency.

To compare the alternative network configurations, for each risk level, the total number of spare parts in the various node inventory buffers is fixed for all four configurations. This constitutes a common denominator for comparison. First, the four inventory buffer sizes—corresponding to the four risk levels—are used as a basis to determine the total number of spare parts dedicated to the system. Next, parts are re-allocated to the various nodes in an effective way such that the selected MOEs are optimized or nearly optimized.

The appropriate network configuration depends on the selected risk level, which is affected by desirable network properties. If the objective is a high level of attainability at each node—measured by 100% PackUp Effectiveness and 0 PartShort—then no-risk inventory buffer sizing is required. No-risk inventory buffers will have a significantly greater range—the number of line items of spare parts in the logistical support package—and depth—the quantity of each spare part in the logistical support package—than other

risk level inventory buffers. Using this risk level, the most efficient network design omits the proposed ESB. If operational flexibility, defined as a system's ability to quickly and effectively respond to changes, or survivability is a high priority, planners should be willing to accept less than maximum attainability to reduce the logistical support footprint at each node. In this situation, low-, medium- or high-risk level buffer sizing is appropriate.

PackUp Effectiveness and PartShort may not improve in tandem as a result of changing the design of the support network. A system that increases the percentage of demands satisfied on the day demanded does not necessarily improve the response time for unsatisfied demand. These two MOEs may require different network configurations to perform most effectively.

As a result of our modeling and analysis, we come to the following conclusions:

(1) For no-risk inventory buffer sizes, ESB0 dominates all other alternative network configurations.

(2) For all non-zero risk levels, if the objective is to maximize PackUp Effectiveness, ESB0 is still the dominating alternative.

(3) For all non-zero risk levels, if the objective is to minimize PartShort, ESB1 is the dominating alternative. Also, any network with an ESB less than five days TRR from the demand nodes will outperform ESB0.

(4) If the ESB is included, performance improves as the TRR between the ESB and the demand nodes is minimized.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Air Combat Element
AOR	Area of Responsibility
CCSP	Common Contingency Support Package
ELAT	Enterprise Logistics Analysis Tool
ESB	Enroute Support Base
FISP	Fly-in Support Package
FOB	Forward Operating Base
FOSP	Follow-on Support Package
FY	Fiscal Year
IMA	Intermediate Maintenance Activity
MAGTF	Marine Air Ground Task Force
MALS	Marine Aviation Logistics Squadron
MALSP	Marine Aviation Logistics Support Program
MOB	Main Operating Base
NIIN	National Item Identification Number
OEF-Afghanistan	Operation Enduring Freedom-Afghanistan
OEF-HOA	Operation Enduring Freedom-Horn of Africa
OIF	Operation Iraqi Freedom
OPLOG	Operational Logistics
PCSP	Peculiar Contingency Support Package
PMALS	Parent Marine Aviation Logistics Squadron
SAMMS	Stand-alone Material Management System
T-AVB	Marine Corps Aviation Logistics Ship
TRR	Time to Reliably Replenish

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I. INTRODUCTION

A. THESIS PURPOSE: EVALUATE MALSP II SUPPORT NETWORK

Due to increased operational requirements in Operation Iraqi Freedom and Operation Enduring Freedom, Marine Corps aviation logistics planners must find innovative ways to improve efficiency of resources. The Marine Aviation Logistics Support Program (MALSP) II is designed specifically to protect the logistical system from uncertain, possibly high variance, demand that could have a significant detrimental impact on the material readiness of deployed aircraft. MALSP II is a pull-based replenishment system that supports packages of spare aircraft parts—called *inventory buffers*—that are determined using demand patterns specific to the operation supported during the *time to reliably replenish* (TRR). TRR is determined by the elapsed time from when a spare part is issued from an inventory buffer until the part is replaced in the inventory buffer. The MALSP II system includes an additional level of supply, which is designated to improve the responsiveness of the logistic system. Since 2005, a MALSP II pilot program has produced positive results; however, the overall design of the logistical support has not yet been evaluated. Using MALSP II conditions, this thesis develops an inter-temporal simulation model that measures the operational effectiveness of four network configurations using four inventory buffer sizing methods. The results of this model and subsequent analysis will assist operational planners select the system configurations and policies that improve the efficiency of available resources and maximize the effectiveness of logistical support to deployed bases.

B. MALSP USED FOR THE PAST 20 YEARS

Marine Corps aviation logistics is in the process of transforming the model used to support deployed operations. For 20 years, the Marine Corps has used MALSP—a model that dictates the necessary people, equipment, spare parts, and mobile containers to deploy in support of contingency operations. Based on monthly averages, MALSP separates 30 days of supply into mobile containers that deploy with the organizational level flying squadron. During those 30 days, the Marine Aviation Logistics Squadron

(MALS) deploys on a support ship (T-AVB) and brings an additional 60 days of logistical support. The end result is an entire Intermediate Maintenance Activity (IMA) with 90 days of supply and repair capability in theatre with a long replenishment chain.

Figure 1:   Intermediate Maintenance Activity operating in expeditionary mode in Middle East (From ASL 2004)

MALSP measures effectiveness using PackUp Effectiveness. This metric calculates the number of demands satisfied at the time demanded as a percentage of overall demand. It does not measure the response time of unsatisfied demands.

Aviation Logistics is comprised of three maintenance levels defined in the Naval Aviation Maintenance Program OPNAVINST 4790.2. The first level is the organizational level. This level performs preventative and planned maintenance on aircraft at regular intervals based on flight hours. Further, the organizational level inspects planes for unplanned maintenance problems. If a problem is identified, the organizational level maintainers remove repairable components and order replacements from the intermediate level. When the repairable component is removed from the

aircraft, it creates a "hole" in the aircraft that makes it non-mission or partial-mission capable until that "hole" is filled. The intermediate level is organized as a MALS comprised of both supply, responsible for maintaining a warehouse of replacement spare parts, and an IMA, responsible for repairing aircraft components. The MALS is responsible for replacing repairable components either by issuing a replacement part or fixing the broken part. If the MALS is unable to repair components, they are sent to the third level—the depot level—for "overhaul" maintenance or disposal.

Prior to MALSP, the Marine Corps did not have a standardized means of organizing and deploying aviation logistics. Developed in 1989 during the Cold War, MALSP was designed to enable the Marine Air Ground Task Force (MAGTF) Air Combat Element (ACE) to deploy with sufficient support while the MALS transported necessary resources to set up a forward logistics base (Delaporte 2007, 4). It is a concept based on deploying in layers and sustaining operations for a prolonged time. Using multiple building blocks, MALSP enabled peace-time aviation logistics units to quickly organize and deploy in support of contingency operations. The mission of MALSP is to identify and integrate necessary spare parts, support equipment, and people to support all aircraft types that could comprise a MAGTF ACE.

MALSP is a push system consisting of four types of standardized support packages intended to support any contingency operation. The Fly-in Support Package (FISP) is designed to support the fly-in echelon aircraft—those that deploy in the initial phase—of the MAGTF ACE for the first 30 days. The FISP is a standalone package intended to sustain the ACE while the intermediate maintenance capability is transported by the aviation logistics support ships. The Common Contingency Support Package (CCSP), Peculiar Contingency Support Package (PCSP), and Follow-on Support Package (FOSP) are designed to provide an additional 60 days of spare parts, mobile facilities with test benches, intermediate maintenance repair capability and support equipment to sustain operations (Delaporte 2007, 4). The CCSP contains aircraft components used on multiple types of aircraft while the PCSP is intended for a single type of aircraft. The FOSP contains support not included in either the CCSP or PCSP but necessary for deployments of longer duration. These packages are pre-determined without knowledge

of the environmental conditions in the theatre, operational tempo or other tactical or operational factors. Inventories of spare parts are determined using past average monthly demand and subject matter expert opinion. Unplanned requirements and re-supply rely on a supply chain with high variation and are dependent on available transportation.

Support packages are designed for each aircraft platform and fit together like building blocks. In garrison, Marine Aircraft Groups are organized by peculiar aircraft; however, contingency operations require composite squadrons with multiple types of aircraft. For example, a Marine Expeditionary Force ACE comprised of CH-46, CH-53, AH-1W and UH-1N helicopters deploys with one CCSP, three FISPs and three PCSPs totaling 95 pallets that weigh over 4800 tons (Delaporte 2007, 5). MALSP results in a large, immobile footprint at the deployed sites to sustain operations.

C.   MALSP II WILL REPLACE MALSP BUT HAS NOT BEEN FULLY EVALUATED YET

MALSP II is designed to protect the logistical support system from uncertain, possibly high variance, demand for spare parts. Further, MALSP II aims to reduce the maintenance repair equipment, mobile facilities and people at the forward operating bases required by legacy MALSP. MALSP II changes business rules and designs the logistical support network to buffer the system from variation and improve the efficiency of using resources. It develops support packages that can be quickly organized to meet specific demand patterns of varying configurations of aircraft for unknown durations.
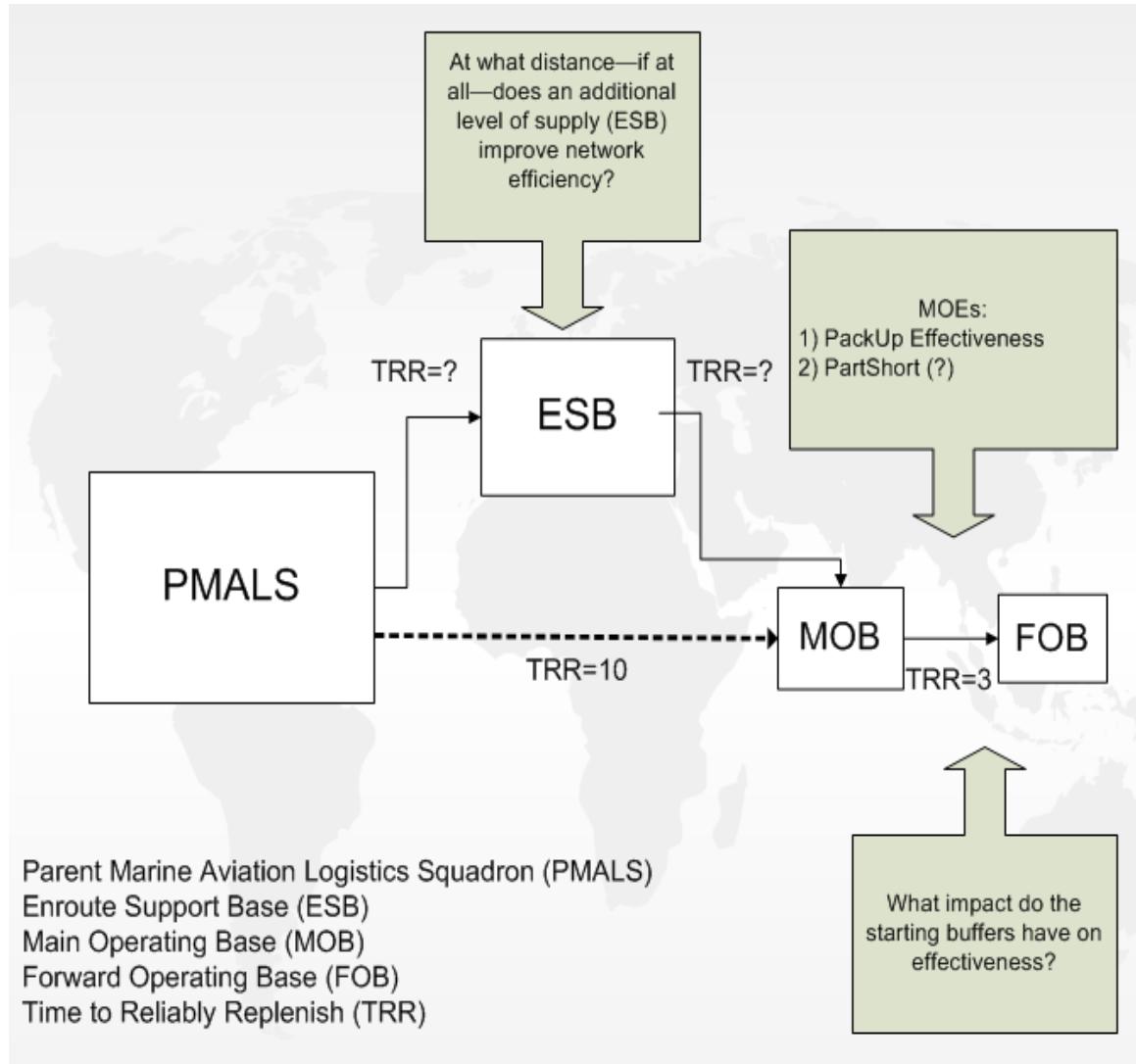
Figure 2: Overview and key questions about the MALSP II logistics support network

MALSP II currently uses the same measure of effectiveness—*PackUp Effectiveness*—as legacy MALSP. Since the goal of MALSP II is to be flexible and responsive, this thesis suggests a new measure of effectiveness—*PartShort*—that counts the number of unsatisfied daily demands to assess overall responsiveness of the system (ASL 2004).

MALSP II dictates a change in business rules. Departing from MALSP's reliance on monthly averages, MALSP II determines the quantity of spare parts—called an *inventory buffer*—allocated to each node using the demand pattern within the re-supply

lead-time called Time to Reliably Replenish (TRR). TRR begins when a spare part is issued for consumption at a maintenance facility, henceforth called demand nodes, and ends when the part is replaced in the inventory buffer at the demand node. Since a shorter TRR reduces the time periods in which demand may occur, one objective of MALSP II is to minimize TRR. Legacy MALSP defines a re-order objective, the maximum inventory at a site, and a re-order point that signals when a re-order is placed. The re-order point is not necessarily reached immediately after each demand. The Marine Corps Aviation Supply Desktop Procedures (MCO P4400.177E) do not explicitly define the frequency the parent node re-supplies the child node. MALSP II requires immediate requests for re-supply from the demand node and daily replenishments from the supply node (Garant 2006, 12). Changing behavior is a necessary part of minimizing TRR, but it also requires a synchronized support network.

MALSP II creates four logistic levels to buffer the system from variation in demands inherent in deployed military operations. The P-level, comprised of the Parent Marine Aviation Logistics Squadron (PMALS), is the highest level. It contains spare parts repair capability and receives spare parts directly from wholesale supply, depots, and the original equipment manufacturers. The next level of supply is the E-level comprised of the Enroute Support Base (ESB). The ESB manages an inventory buffer for the forward deployed nodes, but does not have local demand. The ESB contains limited or no spare parts repair capability. The next level of supply is the M-level comprised of the Main Operating Base (MOB). The MOB is located in the theater of operations, known as the Area of Operations (AOR), with the organizational level flying squadrons. It contains limited or no spare parts repair capability. It contains an inventory buffer both to satisfy local demand and to re-supply the next level of supply, the F-level which is comprised of the Forward Operating Base (FOB). The FOB is also located in the theater of operations with a detachment of planes from the organizational flying squadron. For example, the FOB at Operation Enduring Freedom-Horn of Africa (OEF-HOA) supported a 4 plane detachment of CH-53 helicopters during FY-08. The FOB has an inventory buffer to satisfy local demand only. The four levels of nodes are based on a

hierarchical structure with increased inventory of spare parts and repair capability at the higher echelons and smaller footprints at the lower echelons (Steward 2008, 41).

MALSP II builds the support network to improve the responsiveness of the system and reduce the footprint at the forward demand nodes. An additional level of supply—the ESB—is added to the network to reduce the long supply chain between the supply nodes and the demand nodes. The ESB is intended to reduce TRR to the M-level thereby reducing the inventory buffer at the demand nodes for planned requirements. Further, the ESB adds an additional supply buffer to the network designed to increase responsiveness for unplanned requirements (Steward 2008, 42). Though historical demand data is useful for planning material requirements, it does not perfectly predict future requirements. By adding this additional inventory buffer, the downstream nodes may have an extra layer of protection from prolonged supply shortages.

MALSP II is a pull system that uses demand patterns to allocate spare parts rather than averages used in traditional push systems such as MALSP. While averages may be useful in steady state low-variance environments, combat operations are characterized by higher uncertainty due to high operational and environmental variability. The following describes the method used by the Enterprise Logistics Analysis Tool (ELAT), developed by Colonel Laurin Eck, USMC (Ret.), to determine inventory buffer sizes (Eck, 2009). The first step is to estimate the probability mass functions (PMF) and cumulative distribution functions (CDF) of demand during various lengths of TRR. The estimates are based on observed in-context data from the various theatres of operation. An example of PMF and CDF is presented in Table 1. From the CDF, four initial levels of spare parts are determined that corresponds to levels of risk accepted by the commander. If a commander is not willing to accept any risk, the maximum observed demand (100th percentile) during the TRR is used as an initial inventory buffer. In Table 1, the no risk inventory buffer is 8 spare parts. The low risk inventory buffer is calculated using the 97th percentile of total demands during TRR. In Table 1, the low risk inventory buffer is 6 spare parts. The medium risk inventory buffer is calculated using the 94.7[th] percentile and the high risk inventory buffer is calculated using the 87th percentile. The medium

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risk and high risk inventory buffers in Table 1 are 5 and 3, respectively. The demand
pattern for initial allowances for spare parts depends on specific contingency conditions.

Demand	PMF	CDF
0	0.589	0.000
1	0.106	0.589
2	0.172	0.694
3	0.006	0.867
4	0.067	0.872
5	0.011	0.939
6	0.028	0.950
7	0.017	0.978
8	0.006	0.994
		1.000

Table 1:   FOB Cumulative Distribution Function for TRR=1 day

MALSP II designs the network to improve the efficiency of available resources
such as transportation, repair capability, spare parts, and people. Using the MALSP II
methodology, some nodes will require less spare parts than legacy MALSP. However,
spare parts comprise a relatively small proportion of the overall support package and
reducing spare parts will only have a small effect on overall footprint. More importantly,
MALSP II aims to reduce the amount of repair equipment, mobile facilities and people
needed at the deployed bases thereby reducing total footprint forward. By applying new
logistical practices and better coordinating the logistical support network, MALSP II
aims to improve the effectiveness of support to multiple, simultaneous contingencies.

D.   THESIS SCOPE: BUILD A MODEL THAT USES DEMAND PATTERN TO DESIGN AND EVALUATE SUPPORT NETWORK

The Deputy Commandant of Aviation Logistics, Support Branch implemented a
MALSP II pilot program in 2005 with the intention to fully implement MALSP II by
2015 (Delaporte 2007, 6). This implementation requires operational planners to select
the system configuration and inventory buffer sizing policy that most efficiently uses
available resources to maximize the effectiveness of logistical support to deployed bases.

This thesis develops an inter-temporal simulation model that measures the
operational effectiveness of four network configurations using the four inventory buffer
sizing methods used in ELAT. It compares results using the traditional goal of PackUp

Effectiveness and a new measure of effectiveness—PartShort—that tracks the number and duration of unsatisfied demands referred to as *holes* in aircraft. Further, the model quantifies the impact on operational effectiveness of the risk levels used by ELAT to develop inventory buffers. It does not address allocation of other resources such as maintenance repair equipment, transportation assets or personnel.

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II.   LITERATURE REVIEW

A.   BACKGROUND ON LEGACY MALSP

Legacy MALSP follows the traditional Economic Lot Size Model introduced by Ford W. Harris in 1915 (Simchi-Levi 2000, 43). According to this model, demand occurs at a known fixed rate and lead time is considered negligible. The goal of this model is to minimize a cost function to achieve maximum profit.

Traditional economic models assume that demand follows a normal distribution. By making this assumption, inventory sizes are determined using average daily demand and standard deviation (Simchi-Levi 2000, 52). By contrast, the MALSP II method of determining inventory buffers does not assume that demand for spare parts follow a normal distribution. Rather than using average demand, the MALSP II method of determining inventory buffers uses demand patterns over time. Though averages may be appropriate in long-term steady-state environments, they do not protect against demand spikes that may prove critical during shorter term military operations.

Legacy MALSP is a push-based supply chain while MALSP II is a pull-based supply chain. Push-based systems rely on long-term forecasts and can lead to an inability to meet changing demand patterns due to increased variability (Simchi-Levi 2000, 118). To offset that risk, push-based systems add a safety level that result in larger inventories. Pull-based systems are demand driven and decrease variability thereby decreasing necessary inventory levels. However, pull-based systems are difficult to implement when lead times are too long to respond quickly to demand signals. Therefore pull-based systems require additional transportation considerations to ensure responsive lead times.

B.   MALSP II IS DESIGNED SPECIFICALLY FOR DEPLOYED OPERATIONAL LOGISTICS ENVIRONMENT

Logistical planning factors are different in a military setting and a business setting. The logistical support network can be specifically designed to accomplish military objectives. Operational logistics (OpLog) is defined as "a collection of means, resources, and organizations and processes that share the common goal of sustaining

campaigns and large-scale military operations. OpLog is designated to sustain battles that are distributed in time and space" (Kress 2002, 40).

Military costs are different than civilian economic costs. Unlike the business logistics model—Economic Order Quantity—the cost function to be minimized in a deployed military setting is nebulous. In the military, cost is anything that limits a unit's fighting ability. For example, a unit with a large logistics tail loses mobility or requires additional transportation capacity, which may hinder operational agility (Kress 2002, 42).

The relative stability of a business logistics flow is not always present in an OpLog system. Uncertainty in military operations is inherent and may lead to large variances in consumption rates. Variability is caused by several factors. The changing combat situation may increase or decrease tempo over time which may affect demand for parts. Further, individual combat units, with differing maintenance practices, are rotated at regular intervals (Kress 2002, 136).

Military planners have three logistics options: obtain the needed resources at the battlefield, deploy resources with the troops prior to operations and employ necessary resources to the battlefield over time (Kress 2002, 10). With improvements in transportation and communication during the past century, the third option has become dominant. However, planners must carefully balance both deployment and employment to ensure resources are available when needed without creating an unnecessarily large logistics tail. Forward deployed logistics units require sustainment as well which causes an increasing cycle of personnel and supplies at the forward deployed site (Kress 2002, 13).

There are many desirable properties of an OpLog support network. Flexibility is defined as a system's ability to quickly and effectively respond to changes in a system. In the context of current operations, these changes include operational tempo and location. As operational tempo increases, demand for parts is likely to increase therefore it is important to have a logistical support network that is responsive to a changing demand pattern. Further, force size increases and decreases by location. A flexible system has the ability to quickly determine the logistical support needed at a location and have spare parts available to deploy.

Attainability is defined as a node's ability to independently satisfy demand. Higher attainability allows a node to remain self-sufficient for a longer period of time (Kress 2002, 63). Larger deployments of spare parts increase a node's attainability.

Survivability describes the degree that logistical assets are vulnerable to enemy's hostile action (Kress 2002, 63). In today's operational environment, logistical support and the people required to maintain support have a higher degree of survivability at nodes other than the demand nodes. Future conflicts may have lower degrees of survivability at the demand nodes and in the transportation system that may affect the desired ratio of deployment and employment.

Logistics efficiency measures the ratio between inputs invested in logistical capability and the estimated operational effectiveness—anything that leads to mission accomplishment (Kress 2002, 42). The objective at the tactical level is to minimize two gaps: the quantity gap and time gap (Kress 2002, 74). When logistical support is synchronized by quantity and time, units will receive sufficient supplies without causing an avoidable loss of fighting ability or impeding another unit's effectiveness (Kress 2002, 68-69).

Achieving these properties requires making tradeoffs between time and quantity. Decreasing response time enables the node to decrease the quantity pre-positioned thereby improving flexibility without a significant loss of attainability (Kress 2002, 68).

Lead-time and uncertainty are important considerations when modeling the OpLog system. Due to large variances caused by uncertainty, mean values are inappropriate planning values at the operational level. Instead, demand pattern must be considered with respect to time. Logistical demand and the available resources that determine lead-time must be coordinated (Kress 2002, 46). Structuring the size and location of rear and forward intermediate nodes are based on mitigating uncertainty caused by demand pattern and lead-time (Kress 2002, 51).

Kress introduces the Logistics Inter-Temporal Network (ITN) Optimization Model that represents the importance of time dependence on logistical support in a deployed environment. This model is specifically designed to account for uncertainty in military operations and the importance that lead-time, defined in MALSP II as TRR,

plays in mitigating that uncertainty. The ITN model determines the deployment and employment of resources by calculating measures of effectiveness. Specifically, the ITN determines the quantity of assets to place at forward nodes and the structure of the supporting network needed to provide sufficient distribution (Kress 2002, 219).

III. ITN SIMULATION MODEL

A.   MODEL DEVELOPMENT

This thesis builds an ITN simulation model based on the Logistics ITN Optimization Model developed by Kress (Kress 2002, 219). The model evaluates the performance of the logistics system under four different network configurations with varying resource allocations using MALSP II design and business rules. It varies the number of echelons of supply nodes, TRR between nodes and starting inventories at each node and then evaluates performance using two measures of effectiveness, PackUp Effectiveness and PartShort.

The network structure of the ITN model is loosely based on current deployed operations—Operation Iraqi Freedom, Operation Enduring Freedom-Afghanistan and Operation Enduring Freedom-Trans Sahara (Horn of Africa)—requiring aviation logistical support. Figure 3 presents the network containing three areas of responsibility (AOR): one MOB supporting one FOB, one MOB supporting two FOBs and a unique node with FOB demand but TRR of a MOB. Four logistics levels are defined: P-level includes PMALS, E-level includes ESB, M-level includes MOBs, and F-level includes FOBs. Though multiple Marine Aviation Logistics Squadrons may provide support, the model simplifies to assume one PMALS supports the network with an unlimited supply of spare parts.

| P-level | E-level | | M-level | F-level |
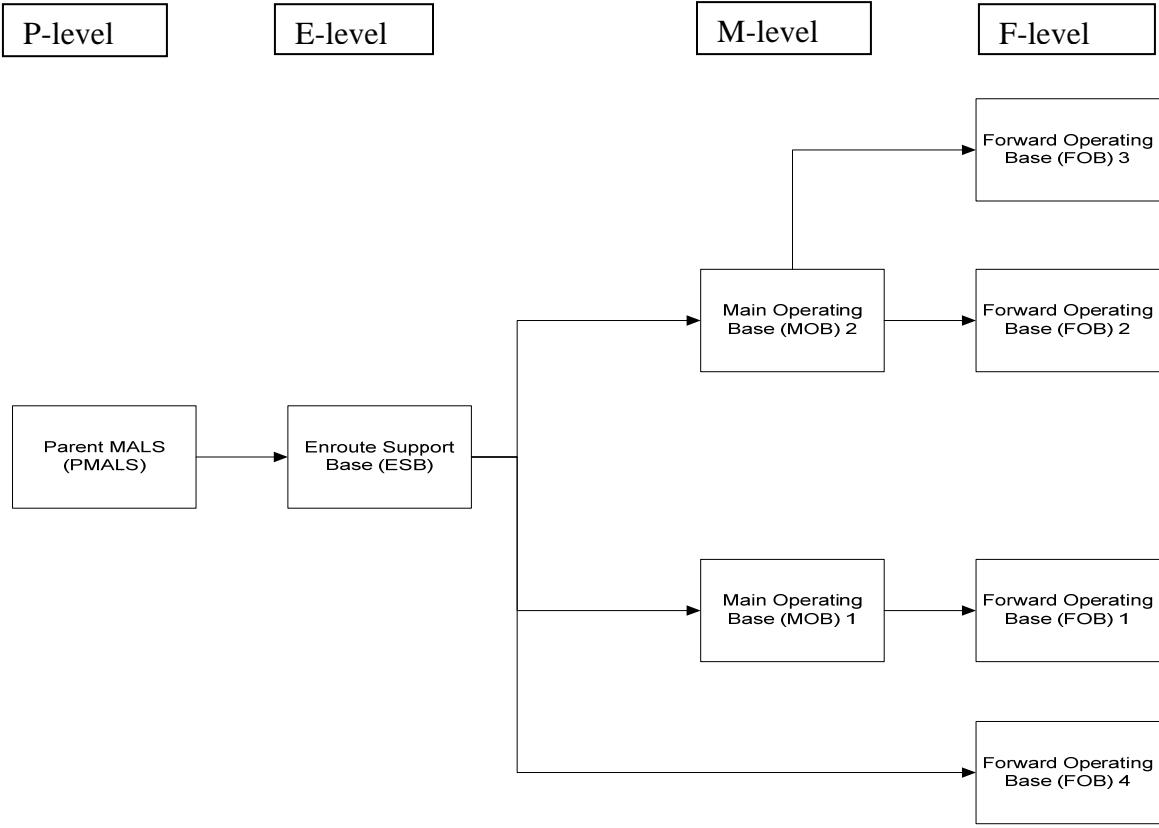
Figure 3:   MALSP II Visual Network

The TRR figures among the various logistics levels are based on values used during fiscal year (FY) 2008 in the MALSP II pilot program. Without an ESB, the TRR between the PMALS and the MOB is 10 days. The TRR between the MOB in Al Asad, Iraq and the FOB in Al Taqadum, Iraq was 3 days. It is assumed that adding an additional node between the PMALS and the MOB will add an extra day of handling time therefore the total TRR from the PMALS to the ESB and from the ESB to the MOB equals 11 days; however, the exact TRR from the PMALS to the ESB and from the ESB to the MOB will vary in our analysis to find the values with best results. It is assumed that the TRR between any MOB and its associated FOB is fixed at 3 days.

The model considers one aircraft part at a time. For each part, four network configurations are modeled. ESB0: the network has no ESB and therefore the TRR from the PMALS to a MOB is 10 days. ESB5: the ESB is added at a distance of 5 days TRR to any MOB and 6 days TRR from the PMALS. ESB3: the ESB is added at a distance of

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3 days TRR to any MOB and 8 days TRR from the PMALS. ESB1: the ESB is added at a distance of 1 day TRR to any MOB and 10 days TRR from the PMALS. Twenty aircraft parts with varying demand patterns are analyzed.

	TRR FOB1	TRR FOB2	TRR FOB3	TRR FOB4	TRR MOB1	TRR MOB2	TRR ESB
ESB0	3	3	3	10	10	10	N/A
ESB5	3	3	3	5	5	5	6
ESB3	3	3	3	3	3	3	8
ESB1	3	3	3	1	1	1	10

Table 2: TRR between nodes for each network configuration

We obtain demand data for the model from recent operations. By design, the MOB supports more aircraft than the FOB and therefore the former will typically have a higher demand pattern than the latter. This thesis uses 12 months of CH-53 demand data. MOB demand data captures a full squadron participating in Operation Iraqi Freedom during FY 2008 obtained from ELAT. FOB demand data captures a four plane detachment participating in Operation Enduring Freedom-Horn of Africa during FY 2008 obtained from the Standalone Material Management System (SAMMS).

Combinations of initial inventory levels for each node in the E-, M-, and F-levels are used to evaluate the network. Using the MALSP II methodology described in Chapter I, the initial inventory associated with each risk level (no, low, medium, and high) is calculated for each node using the TRR values associated with each network configuration described in Table 2. The model evaluates performance measures of the network for each allocation of spare parts.

We calculate two measures of effectiveness (MOE)—PackUp Effectiveness and PartShort. PackUp Effectiveness is the current metric used by the Marine Corps to evaluate the effectiveness of aviation logistical support in a deployed setting. It calculates the percentage of demands over a given time period (weekly, monthly, etc) that a node is able to satisfy demand for spare parts from its inventory buffer at the time when the order is placed. If the node is unable to satisfy demand, the requirement will exist until parts are received from a higher logistics level to fill that hole. The value of PackUp

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Effectiveness is computed as the ratio between the number of parts issued on the day ordered and the total number of parts demanded during the time period. For example, if 5 parts are demanded in a certain day and only 3 parts are issued from the inventory buffer, PackUp Effectiveness for that day is 3/5 or 60%. PartShort is the summation of unfilled daily demands during the observed period. PartShort measures the response time for a node to recover from a supply shortage. If each part ordered is a missing part from an aircraft, which is therefore unable to fly, PartShort represents the magnitude and duration of holes in aircraft. For example, if 5 parts are demanded in a certain day and only 3 parts are issued from the inventory buffer, PartShort for that day is 2. If no replenishments are received and no demands occur the next day, PartShort for the next day is 2. The total PartShort for the two days is 2 + 2 or 4.

B.   RULES USED IN THE ITN SIMULATION MODEL

The ITN model uses the network topology depicted in Figure 3, and the supply rules applicable to MALSP II to perform Monte Carlo simulation to evaluate the benefit of an ESB, and the effect of its relative location, with respect to four responsiveness risk levels. The model also evaluates the expected performance of different inventory allocations. Using historical demand data, the model first builds cumulative distribution functions of daily demands at the M-level and F-level nodes and then generates randomized daily demand values for the simulation. Initial inventory buffers for the various risk levels are determined based on ELAT's methodology described in Chapter I and the TRRs between nodes. For example, if the risk level is low, and the TRR from a node to the higher logistics level is 5 days then the buffer size in that node is the 97th percentile of the observed demand values during all 5 day time periods using 360 days of observed demand data. The simulation follows standard logistical rules, which prioritize how parts are consumed and distributed. The simulation proceeds as follows: spare parts are consumed as demanded (if available), immediately re-ordered and replenishment spare parts are received within each node's TRR consistent with MALSP II. A detailed description of the simulation is given below. Four network configurations are compared using the aforementioned two MOEs. Each AOR calculates the MOEs separately and then MOEs are aggregated to evaluate total system performance.

Since the MOB is responsible for satisfying local demands and re-supplying its child FOB(s), priorities are assigned that ensure spare parts are used to fill actual holes in aircraft before filling shortages in inventory buffers. Holes in aircraft at the FOBs take precedence over holes in aircraft at the MOBs. If the MOB and its child FOB have demands in the same day that they are unable to satisfy from their local inventory buffers—both have aircraft with holes that are unable to fly—the MOB ships spare parts to the FOB before filling internal demand. However, if the FOB satisfies demand from its inventory buffer or has sufficient spare parts in the shipping pipeline to satisfy supply shortages, the MOB satisfies MOB demand before sending inventory replenishment to the FOB. MOB2 prioritizes FOB2 over FOB3 (see Figure 3). The flow of spare parts only flows from the parent node to the child node. Once a part is sent downstream it does not go back to the parent. Nodes within the same level (M- or F-) do not send spare parts to each other.

In cases where multiple AORs require parts, the ESB fills holes in aircraft before shortages in inventory buffers. If multiple AORs have holes in aircraft, the ESB will fill FOB4 requirements then MOB2 then MOB1. The ESB does not send parts directly to FOB1, FOB2, or FOB3.

C.   MODEL FORMULATION

1.   Indices and Sets

t	time periods, $t \in \{0,1,2,...,360\}$
m	MOB nodes in the network, $m \in \{1, 2\}$
f	FOB nodes in the network, $f \in \{1, 2,3,4\}$
$F(m)$	Set of FOBs that belong to MOB m

2.   Data

trr_f	Time to reliably replenish FOB f from its MOB
trr_m	Time to reliably replenish MOB m from a higher echelon
trr_e	Time to reliably replenish ESB from the PMALS
$d_f(t)$	demand at FOB f at time t

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$e_m(t)$ demand at MOB m at time t

$Buffer_f$ initial inventory buffer of FOB f

$Buffer_m$ initial inventory buffer of MOB m

$Buffer_e$ initial inventory buffer of ESB

3. State Variables

$Y_f(t)$ supply at FOB f at time t

$X_m(t)$ supply at MOB m at time t

$Z_e(t)$ supply at ESB at time t

$R_f(t)$ supply shipped to FOB f from its parent MOB m at time t

$TR_f(t)$ total supply in pipeline to FOB f at time t

$R_m(t)$ supply shipped to MOB m from ESB or PMALS at time t

$TR_m(t)$ total supply in pipeline to MOB m at time t

$R_e(t)$ supply shipped to ESB from PMALS at time t

$TR_e(t)$ total supply in pipeline to ESB at time t

$\text{PartShort}_f(t)$ number of parts short at FOB f at time t

$\text{PartShort}_m(t)$ number of parts short at MOB m at time t

$issue_f(t)$ number of parts issued at FOB f at time t

$issue_m(t)$ number of parts issued at MOB m at time t

4. Algorithm

The algorithm described below is accompanied with pseudo-code. During each time period, each node begins with supply from the end of the previous time period. The FOB can then receive replenishment—increase supply—and fill demands—decrease supply. The MOB can receive replenishment—increase supply—and fill local demand or send supply to the FOB—decrease supply. There are two reasons a parent ships supply

to its child: fill holes in aircraft and fill shortages in inventory buffer. Holes in aircraft have a higher priority than shortages in inventory buffer. If the supply at a node is less than 0, $Y_f(t) < 0$ or $X_m(t) < 0$, then there is a hole in aircraft. The sequence of actions simulated in our model is determined by priorities based on the needs at each node, as described in section B of this chapter. The simulation of ESB0—the network without an ESB—is described below using a verbal description and pseudo-code.

(1) On day1, supply at each node is set equal to its inventory buffer. Initially, there is no supply in the shipping pipeline to any node.

$X_m(t) \leftarrow Buffer_m$

$Y_f(t) \leftarrow Buffer_f$

$TR_m(t) \leftarrow 0$

$TR_f(t) \leftarrow 0$

(2) At the beginning of each time period t, the MOB and the FOB start with the supply at the end of time period $t-1$. The MOB and the FOB receive supply shipped from their parent exactly TRR days prior. The supply at each node is incremented and the total supply in the shipping pipeline to each node is decremented. If the time period is not greater than the node's TRR or there was no supply shipped TRR days prior, the node does not receive replenishment during that time period.

If $(t > trr_m)$

$X_m(t) \leftarrow X_m(t-1) + R_m(t - trr_m)$

$TR_m(t) \leftarrow TR_m(t-1) - R_m(t - trr_m)$

End if

If $(t > trr_f)$

$Y_f(t) \leftarrow Y_f(t-1) + R_f(t - trr_f)$

$TR_f(t) \leftarrow TR_f(t-1) - R_f(t - trr_f)$

End if

(3) Next, the FOB's demand is subtracted from the FOB's supply. If demand exceeds supply, the FOB's supply reflects a negative number indicating holes in aircraft. If the FOB's unfilled demand (the absolute value of the FOB's negative supply) is greater than the supply already in the shipping pipeline to the FOB and the MOB has spare parts (supply at the MOB is greater than 0), the MOB ships parts to the FOB exclusively to fill holes in aircraft. Total supply in the shipping pipeline to the FOB is incremented. The quantity shipped from the MOB to the FOB is decremented from the MOB's supply.

$Y_f(t) \leftarrow Y_f(t) - d_f(t)$

If $(Y_f(t) < 0$ and $X_m(t) > 0)$

$R_f(t) \leftarrow$ Max $[0,$ Min $($Abs $(Y_f(t)) - TR_f(t), X_m(t))]$

$TR_f(t) \leftarrow TR_f(t) + R_f(t)$

$X_m(t) \leftarrow X_m(t) - R_f(t)$

End if

(4) Next, the MOB's demand is subtracted from the MOB's supply. If demand exceeds supply, the MOB's supply reflects a negative number indicating holes in aircraft.

$X_m(t) \leftarrow X_m(t) - e_m(t)$

(5) If the MOB's supply is greater than 0, it ships the FOB inventory replenishment that is not already in shipping pipeline. Total supply in the shipping pipeline to the FOB is incremented. The quantity shipped from the MOB to the FOB is decremented from the MOB's supply.

If ($X_m(t) > 0$)

$$R_f(t) \leftarrow R_f(t) + \text{Min} ((\,Buffer_f - Y_f(t) - TR_f(t)\,), X_m(t))$$

$$TR_f(t) \leftarrow TR_f(t) + R_f(t)$$

$$X_m(t) \leftarrow X_m(t) - R_f(t)$$

End if

(6) Last, if the supply at the MOB and the supply in the shipping pipeline to the MOB is less than the MOB's inventory buffer or supply at the FOB and the supply in the shipping pipeline to the FOB is less than the FOB's inventory buffer, the PMALS ships supply to the MOB. The total supply in the shipping pipeline to the MOB is incremented.

$$R_m(t) \leftarrow (\,Buffer_m - X_m(t) - TR_m(t)\,) + (\,Buffer_f - Y_f(t) - TR_f(t)\,)$$

$$TR_m(t) \leftarrow TR_m(t) + R_m(t)$$

(7) At the end of each time period t, the simulation calculates variables used to compute MOEs. At this point, $d_f(t)$ is the demand that has already occurred at FOB f during time period t and $Y_f(t)$ is the resulting supply at the end of time period t.

Description: PartShort

PartShort is calculated each day and added to the previous day's total. First, the variables are initialized to 0. If the supply at the FOB at the end of time t is negative, the number of holes in aircraft is equal to the absolute value of supply at the FOB. For example, if the FOB supply is -3 then there are 3 aircraft with holes. PartShort represents the number of aircraft with holes.

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$\text{PartShort}_f(t) \leftarrow 0$

If $(Y_f(t) < 0)$

$\text{PartShort}_f(t) \leftarrow \text{abs}(Y_f(t))$

End if

Description: Issue

An issue is used to calculate PackUp Effectiveness. An issue occurs only if demand is filled during the time period demanded. Partial issues are allowed. If a squadron orders 8 parts and the FOB fills 5 in that time period, issues for that time period equals 5.

If $(d_f(t) > 0)$ and $(Y_f(t) >= 0)$

$issue_f(t) \leftarrow d_f(t)$

End if

If $(d_f(t) > 0)$ and $(Y_f(t) < 0)$ and $(\text{Abs}(Y_f(t)) < d_f(t))$

$issue_f(t) \leftarrow d_f(t) - \text{Abs}(Y_f(t))$

End if

5.   Measures of Effectiveness

Description: PartShort is the summation of parts short during each time period.

(1) $\text{PartShort} = \sum_t \text{PartShort}_f(t)$

Description: PackUp Effectiveness is the summation of all issues divided by the summation of all demands.

(2) $\text{PackUp Effectiveness} = \sum_t issue_f(t) / \sum_t d_f(t)$ (if $\sum_t d_f(t) > 0$)

D.   EXAMPLES OF MEASURES OF EFFECTIVENESS

Table 3 depicts a CH-53 wheel (NIIN: 014290072) for MOB1 and FOB1 using ESB0 for 30 days. MOEs for Day1 through Day6 are described below using ESB0:

$Buffer_m = 5$; $trr_m = 10$

$Buffer_f = 1$; $trr_f = 3$

$TR_f(t) = 0$

$TR_m(t) = 0$

Day 1 (*t=1*): On day 1, each node's supply begins at full inventory buffer. No demand occurs. No replenishments are received because the time period is less than either node's TRR. Each node's supply does not change during day 1. PartShort = 0 and PackUp Effectiveness is N/A because $\sum Demand$ is not greater than 0.

$Y_f(1)= Buffer_f = 1$

$X_m(1)= Buffer_m = 5$

$d_f(t)=0$

$e_m(t)=0$

PartShort $(1) = 0$; $\sum PartShort = 0$

Issues $(1) = 0$; $\sum Issues = 0$

Demand $(1) = 0$; $\sum Demand = 0$

PackUp Effectiveness = N/A ($\sum Demand$ is not greater than 0)

Day 2 (*t=2*): On day 2, each node's supply begins at the same number it ended day 1. No demand occurs and no replenishments are received at the FOB. The MOB receives a demand for 1 part and its supply is updated. PartShort is unchanged. Issues and Total Demand are updated to reflect 1 each. PackUp Effectiveness is updated to reflect 1 issue/1 demand or 100%.

$Y_f(2)= Y_f(1) = 1$

$X_m(2)=X_m(1) = 5$

$d_f(2)=0$

$e_m(2)=1$

$X_m(2)= 5\text{-}1 = 4$

PartShort $(2) = 0$; $\sum PartShort = 0$

Issues (2) = 1; $\sum$ *Issues* = 1

Demand (2) = 1; $\sum$ *Demand* = 1

PackUp Effectiveness = $\sum$ *Issues* / $\sum$ *Demand* = 1/1 = 100%

Day 3 ($t=3$): On day 3, each node's supply begins at the same number it ended day 2. No demand occurs and no replenishments are received at either the FOB or the MOB. PackUp Effectiveness and PartShort are unchanged.

$Y_f(3) = Y_f(2) = 1$

$X_m(3) = X_m(2) = 4$

$d_f(3) = 0$

$e_m(3) = 0$

PartShort (3) = 0; $\sum$ *PartShort* = 0

Issues (3) = 0; $\sum$ *Issues* = 1

Demand (3) = 0; $\sum$ *Demand* = 1

PackUp Effectiveness = $\sum$ *Issues* / $\sum$ *Demand* = 1/1 = 100%

Day 4 ($t=4$): On day 4, each node's supply begins at the same number it ended day 3. No demand occurs and no replenishments are received at either the FOB or the MOB. PackUp Effectiveness and PartShort are unchanged.

$Y_f(4) = Y_f(3) = 1$

$X_m(4) = X_m(3) = 4$

$d_f(4) = 0$

$e_m(4) = 0$

PartShort (4) = 0; $\sum$ *PartShort* = 0

Issues (4) = 0; $\sum$ *Issues* = 1

Demand (4) = 0; $\sum$ *Demand* = 1

PackUp Effectiveness = $\sum$ *Issues* / $\sum$ *Demand* = 1/1 = 100%

Day 5 (*t=5*): On day 5, each node's supply begins at the same number it ended day 4. The FOB has a demand of 3 and issues 1 from its inventory buffer. The FOB has 2 "holes" in aircraft. The MOB ships the FOB 3 parts to fill both "holes" in aircraft and shortage in inventory buffer. The MOB orders a replenishment of 3 parts from the PMALS. PartShort is updated to reflect 2 during this time period and a total of 2 during the simulation. Issues are updated to reflect 1 during this time period and a total of 2 during the simulation. Demand during this time period is updated to reflect 3 and total during the simulation is updated to reflect 4. PackUp Effectiveness is updated to reflect 2 issues/ 4 demands or 50%.

$Y_f(5)= Y_f(4) = 1$

$X_m(5)=X_m(4) =4$

$d_f(5)=3$

$Y_f(5)= 1\text{-}3= \text{-}2$

$R_f(5)=3$

$TR_f(5)=3$

$X_m(5)= 4 - R_f(5)= 4\text{--}3 =1$

$e_m(5)=0$

$X_m(5)= 1\text{-}0= 1$

$R_m(5)=3$

$TR_m(5)=1+3=4$

$PartShort\ (5) = 2;\ \sum PartShort = 2$

$Issues\ (5) = 1;\ \sum Issues = 2$

$Demand\ (5) =3;\ \sum Demand = 4$

$PackUp\ Effectiveness = \sum Issues / \sum Demand = 2/4= 50\%$

Day 6 (*t=6*): On day 6, each node's supply begins at the same number it ended day 5. Neither the MOB nor the FOB receives replenishment or demand. PartShort reflects 2 during this time period and a total of 4 during the simulation. PackUp Effectiveness is unchanged.

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$Y_f(6) = Y_f(5) = -2$

$X_m(6) = X_m(5) = 1$

$d_f(6) = 0$

$e_m(6) = 0$

$PartShort\ (6) = 2;\ \sum PartShort = 4$

$Issues\ (6) = 0;\ \sum Issues = 2$

$Demand\ (6) = 0;\ \sum Demand = 4$

$\text{PackUp Effectiveness} = \sum Issues / \sum Demands = 2/4 = 50\%$

E. EXAMPLE OUTPUT

t	$Buffer_f$	$d_f(t)$	$Y_f(t)$	$R_f(t)$	$TR_f(t)$	$Buffer_m$	$e_m(t)$	$X_m(t)$	$R_m(t)$	$TR_m(t)$	Part Short	issues	total demand	P-Up Effect
1	1.00	0.00	1.00	0.00	0.00	5.00	0.00	5.00	0.00	0.00	0.00	0.00	0.00	NA
2	1.00	0.00	1.00	0.00	0.00	5.00	1.00	4.00	1.00	1.00	0.00	1.00	1.00	1.00
3	1.00	0.00	1.00	0.00	0.00	5.00	0.00	4.00	0.00	1.00	0.00	1.00	1.00	1.00
4	1.00	0.00	1.00	0.00	0.00	5.00	0.00	4.00	0.00	1.00	0.00	1.00	1.00	1.00
5	1.00	3.00	-2.00	3.00	3.00	5.00	0.00	1.00	3.00	4.00	2.00	2.00	4.00	0.50
6	1.00	0.00	-2.00	0.00	3.00	5.00	0.00	1.00	0.00	4.00	4.00	2.00	4.00	0.50
7	1.00	0.00	-2.00	0.00	3.00	5.00	0.00	1.00	0.00	4.00	6.00	2.00	4.00	0.50
8	1.00	0.00	1.00	0.00	0.00	5.00	0.00	1.00	0.00	4.00	6.00	2.00	4.00	0.50
9	1.00	0.00	1.00	0.00	0.00	5.00	1.00	0.00	1.00	5.00	6.00	3.00	5.00	0.60
10	1.00	0.00	1.00	0.00	0.00	5.00	0.00	0.00	0.00	5.00	6.00	3.00	5.00	0.60
11	1.00	1.00	0.00	0.00	0.00	5.00	3.00	-3.00	4.00	9.00	9.00	4.00	9.00	0.44
12	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	11.00	4.00	9.00	0.44
13	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	13.00	4.00	9.00	0.44
14	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	15.00	4.00	9.00	0.44
15	1.00	0.00	0.00	0.00	0.00	5.00	2.00	-1.00	2.00	7.00	16.00	5.00	11.00	0.45
16	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-1.00	0.00	7.00	17.00	5.00	11.00	0.45
17	1.00	1.00	-1.00	0.00	0.00	5.00	1.00	-2.00	2.00	9.00	20.00	5.00	13.00	0.38
18	1.00	0.00	-1.00	0.00	0.00	5.00	1.00	-3.00	1.00	10.00	24.00	5.00	14.00	0.36
19	1.00	0.00	-1.00	1.00	1.00	5.00	0.00	-3.00	0.00	9.00	28.00	5.00	14.00	0.36
20	1.00	0.00	-1.00	0.00	1.00	5.00	1.00	-4.00	1.00	10.00	33.00	5.00	15.00	0.33
21	1.00	0.00	-1.00	0.00	1.00	5.00	2.00	-2.00	2.00	8.00	36.00	5.00	17.00	0.29
22	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	38.00	5.00	17.00	0.29
23	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	40.00	5.00	17.00	0.29
24	1.00	0.00	0.00	0.00	0.00	5.00	0.00	-2.00	0.00	8.00	42.00	5.00	17.00	0.29
25	1.00	0.00	0.00	0.00	0.00	5.00	0.00	0.00	0.00	6.00	42.00	5.00	17.00	0.29
26	1.00	0.00	0.00	0.00	0.00	5.00	1.00	-1.00	1.00	7.00	43.00	5.00	18.00	0.28
27	1.00	0.00	0.00	1.00	1.00	5.00	0.00	0.00	0.00	5.00	43.00	5.00	18.00	0.28
28	1.00	0.00	0.00	0.00	1.00	5.00	0.00	1.00	0.00	4.00	43.00	5.00	18.00	0.28
29	1.00	0.00	0.00	0.00	1.00	5.00	0.00	1.00	0.00	4.00	43.00	5.00	18.00	0.28
30	1.00	0.00	1.00	0.00	0.00	5.00	0.00	2.00	0.00	3.00	43.00	5.00	18.00	0.28

Table 3: NIIN: 014290072; ESB0: FOB TRR=3, MOB TRR=10

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IV. RESULTS AND ANALYSIS

A. SUMMARY OF RESULTS

Evaluating the design of the logistical support network and the allocation of resources to its various nodes requires prioritizing desirable network properties described in Chapter II. The results of this thesis focus on one property—efficiency—defined as the ratio between inputs invested in logistics capability and estimated operational effectiveness (Kress 2002, 42) measured, in our case, by two MOEs, described in Chapter III: (1) PackUp Effectiveness represents the percentage of demands satisfied on the day demanded and (2) PartShort represents the magnitude and duration of unsatisfied demands. The system's goal is to produce the highest possible value of PackUp Effectiveness and the smallest possible value of PartShort, while constraining the logistical footprint. The model compares the four network configurations described in Chapter III: ESB0 represents the network without an ESB. The other three configurations assume the existence of an ESB and they differ in terms of distance, measured by TRR, from the PMALS and the MOBs: ESB5 is 5 days from the MOBs and 6 days from the PMALS, ESB3 is 3 and 8 days, respectively, and ESB1 is 1 day from the MOBs and 10 days from the PMALS. Each configuration is modeled using each one of the four risk levels—no-risk, low-risk, medium-risk, high-risk—used in ELAT to determine inventory buffers, described in Chapter I. Each instance of the simulation runs for 360 days and is replicated 20 times. The model computes the values of the two MOEs for each combination of network configuration and risk level. The model is applied to 20 different spare parts

This thesis evaluates both the design of the logistical support network and the impact of selecting a certain risk level for inventory buffer sizing. Both MOEs—PackUp Effectiveness and PartShort—quantify the improvement gained by allocating additional spare parts to each node in the network. If operational planners prioritize efficiency above other desirable network properties, these results may help select the appropriate risk level to use when determining inventory buffers, as shown and discussed later on. For each one of the 20 spare parts, the analysis follows the following steps:

(1) For inventory buffer sizes determined by ELAT with respect to the four risk levels and the various values of TRR that correspond to the four network configurations we simulate demands and compute the corresponding values of PackUp Effectiveness and PartShort. Note that the total number of parts in all buffers may vary from one configuration to another.

(2) To facilitate simple efficiency comparisons among the network configurations, for each risk level, the total number of spare parts in the various node inventory buffers is fixed for all four configurations. This constitutes a common denominator for comparison. First, the four inventory buffer sizes are used as a basis to determine the total number of spare parts dedicated to the system. Next, parts are re-allocated to the various nodes to find the inventory buffer sizes at each node that produce the highest values of the selected MOEs for the entire system using the ITN simulation model. Each network configuration is ranked from 1(best) to 4(worst) for each spare part based on the selected MOE. Then, the ranking for all 20 parts are averaged to assign an overall average rank to each network configuration. Also, the frequency of ranks is presented for each network configuration and buffer size. In the case of a tie, the lower rank is assigned to each network configuration.

The results of the analysis with respect to the 20 selected spare parts and the four risk levels indicate that no network configuration dominates the others throughout. The priority ranking of the four alternatives depend on the particular risk level used to determine inventory buffers and the selected MOE. The priority ranking is independent of the frequency of demand for individual spare parts analyzed. Average rankings are displayed in Figures 4 and 5 below. The frequency of ranks using each network configuration based on PartShort is displayed in Figures 6, 7, 8 and 9. The frequency of ranks using each network configuration based on PackUp Effectiveness is displayed in Figures 10, 11, 12 and 13. Using no-risk inventory buffer sizing, ESB0 generally requires less total number of parts in the support network than the other configurations. Using any other risk level of buffer sizing—low, medium or high—results in different prioritizations based on the selected MOE. Using low, medium or high risk level inventory buffer sizing, ESB0 produces the highest value of PackUp Effectiveness.

Using low, medium or high risk level inventory buffer sizing, ESB1 produces the least number of PartShort. Generally, if the ESB is used in the network, effectiveness decreases as the ESB moves farther from the demand nodes and closer to the PMALS. ESB3 has fewer PartShort than ESB0. ESB5 has approximately equal PartShort as ESB0.
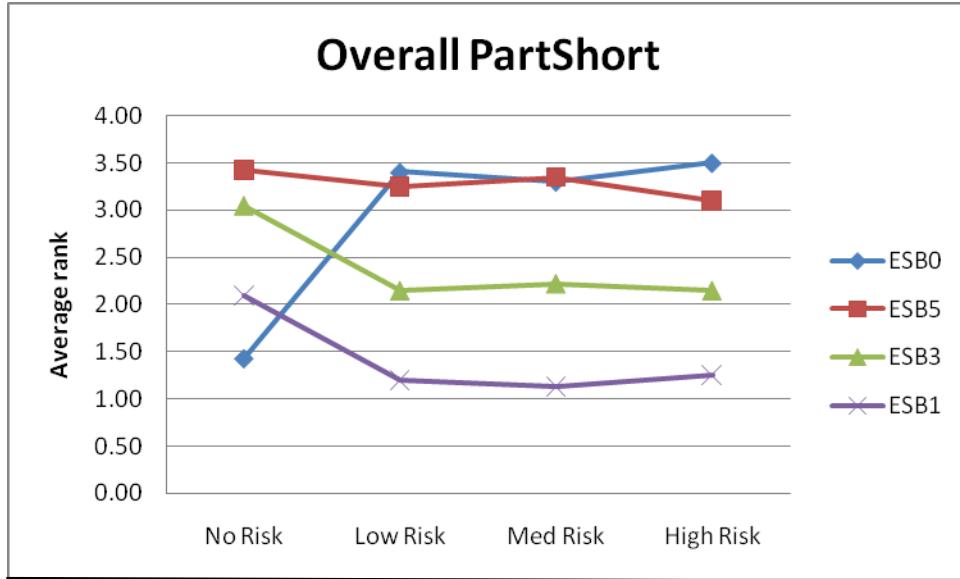
Figure 4:   Overall average ranks based on PartShort using the four network
configurations and four inventory buffer sizing risk levels
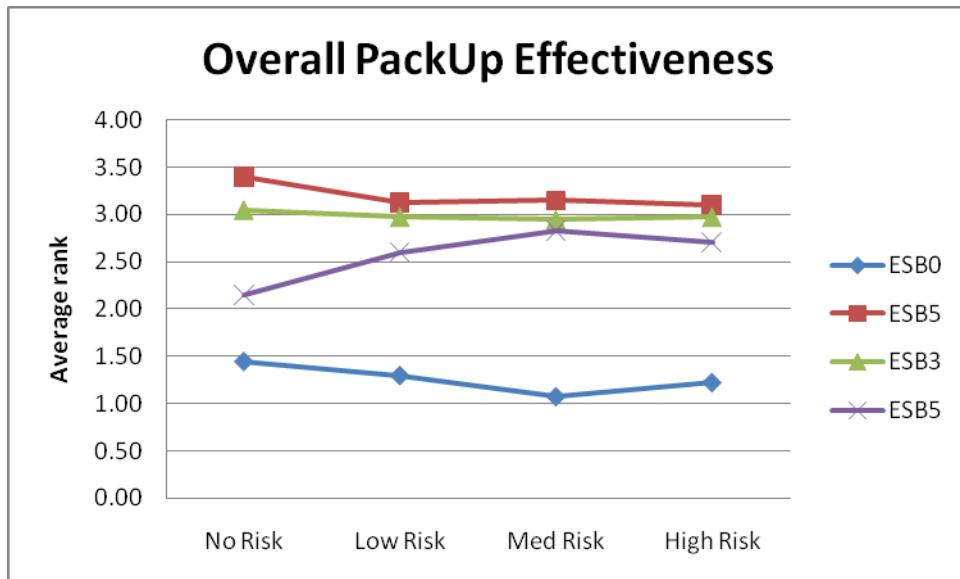
Figure 5:   Overall average ranks based on PackUp Effectiveness using the
four network configurations and four inventory buffer sizing risk levels

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PackUp Effectiveness and PartShort do not necessarily improve in tandem as a result of changing the design of the support network. A system that increases the percentage of demands satisfied on the day demanded does not necessarily improve the response time for unsatisfied demand. Considering each one of these two MOEs may result in different network configurations. A simple example illustrates this finding. The logistical system has a choice between two network designs: ESB0 deploys more parts to the MOB but has a 10 day TRR between the PMALS and the MOB while ESB3 deploys fewer parts to the MOB but has a 3 day TRR between the ESB and the MOB. Assume the MOB using both configurations has a demand of 10 parts. Using ESB0, the MOB issues 7 parts from its inventory buffer yielding 70% PackUp Effectiveness. However, each part not issued the day ordered takes 10 days to arrive resulting in PartShort of 3*10=30. Using ESB3, the MOB only issues 4 parts from its inventory buffer yielding a 40% PackUp Effectiveness. However, each part not issued the day ordered takes 3 days to arrive resulting in PartShort of 6*3=18. While ESB0 has a significantly higher PackUp Effectiveness, ESB3 has fewer (better) PartShort.

Twenty spare parts with varying demand patterns, categorized into three demand levels, are analyzed. Demand is categorized as low if the total demand during 360 days was three or less, medium if the total demand is between four and ten parts and high if the total demand is more than ten parts. Nine parts analyzed represent moderate or high demand at both the MOB and FOB. Nine parts analyzed represent moderate or low demand at both the MOB and FOB. Two parts represent high MOB demand but low FOB demand.

MOEs are calculated for each AOR illustrated in Figure 3 in Chapter III. MOB1 and FOB1 produce one result for each MOE for each network configuration modeled. MOB2, FOB2, and FOB3 produce one result for each MOE for each network configuration modeled. FOB4 produces its own MOEs for each network configuration modeled. System performance is evaluated by computing the MOEs for all three AORs together.

Low-demand parts and high-demand parts are separated to examine if both demand patterns perform the same using the four network configurations. There is not a

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significant difference between results for low- and high-demand parts. The above summary of results applies to both high-demand and low-demand parts.

Two spare parts are used to illustrate results for high- and low-demand aircraft parts. A gyroscope (NIIN: 010632830) represents a part with high MOB demand, ordered 117 times at OIF during FY-08, and moderate FOB demand, ordered 7 times at OEF-HOA. A gearbox assembly (NIIN: 014117040), which was the most expensive part ordered during either OIF or OEF-HOA, represents a part with low demand at both the MOB and FOB. The gearbox assembly was ordered 3 times during OIF during FY-08 and once during OEF-HOA.

Frequency of ranks using no-risk inventory buffer sizes based on PartShort

RANK	1	2	3	4
ESB0	15	5	0	0
ESB5	1	6	7	6
ESB3	1	9	10	0
ESB1	9	10	0	1
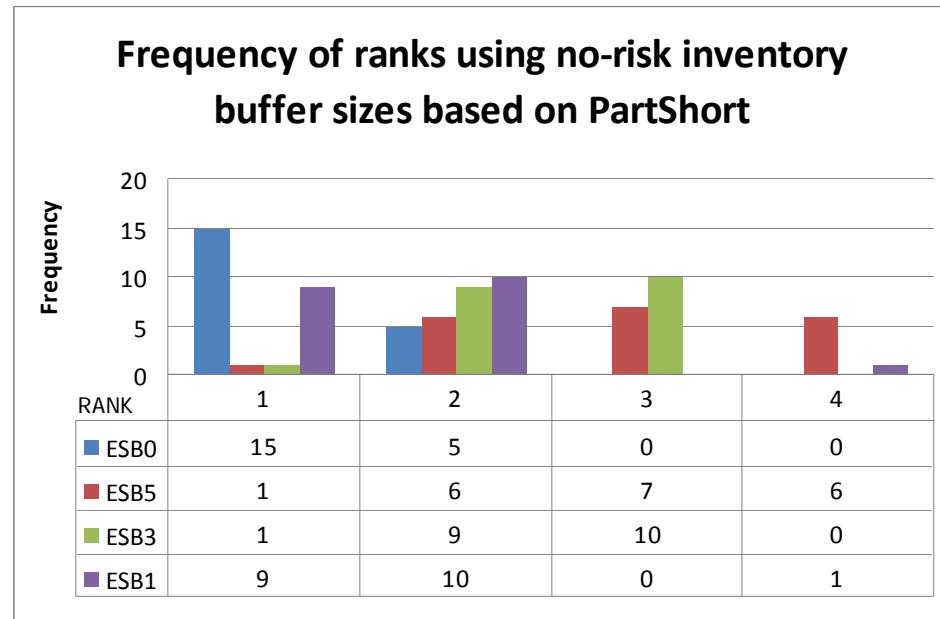
Figure 6:   Frequency of ranks using no-risk inventory buffer sizes based on PartShort

Frequency of ranks using low-risk inventory buffer sizes based on PartShort

RANK	1	2	3	4
ESB0	0	5	5	10
ESB5	3	1	8	8
ESB3	5	13	2	0
ESB1	20	0	0	0
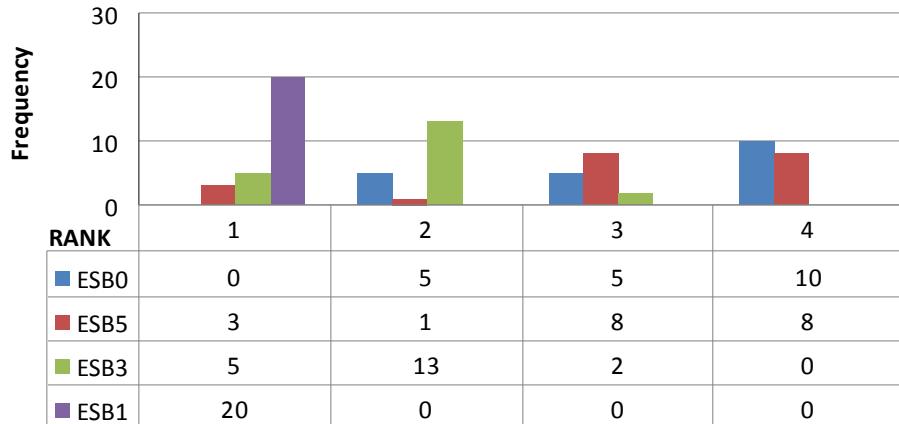
Figure 7:   Frequency of ranks using low-risk inventory buffer sizes based on PartShort

Frequency of ranks using medium-risk inventory buffer sizes based on PartShort

RANK	1	2	3	4
ESB0	2	4	4	10
ESB5	1	2	9	8
ESB3	2	16	2	0
ESB1	20	0	0	0
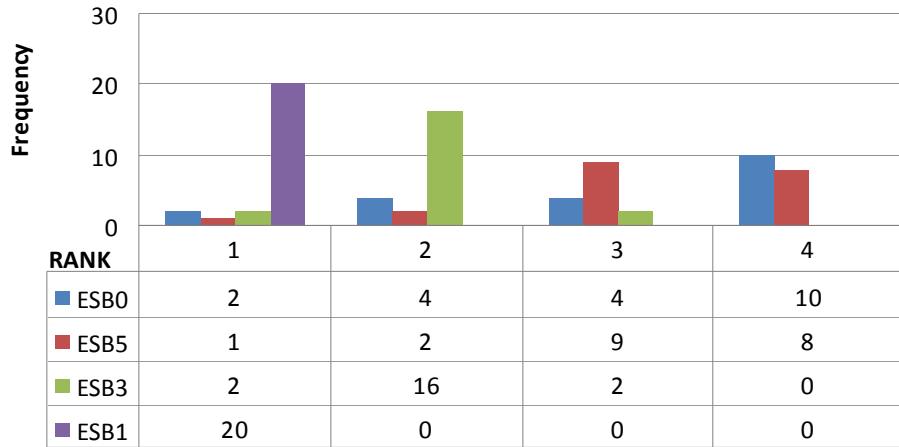
Figure 8:   Frequency of ranks using medium-risk inventory buffer sizes based on PartShort

Frequency of ranks using high-risk inventory buffer sizes based on PartShort

RANK	1	2	3	4
ESB0	1	3	3	13
ESB5	0	2	16	2
ESB3	0	18	2	0
ESB1	17	2	1	0
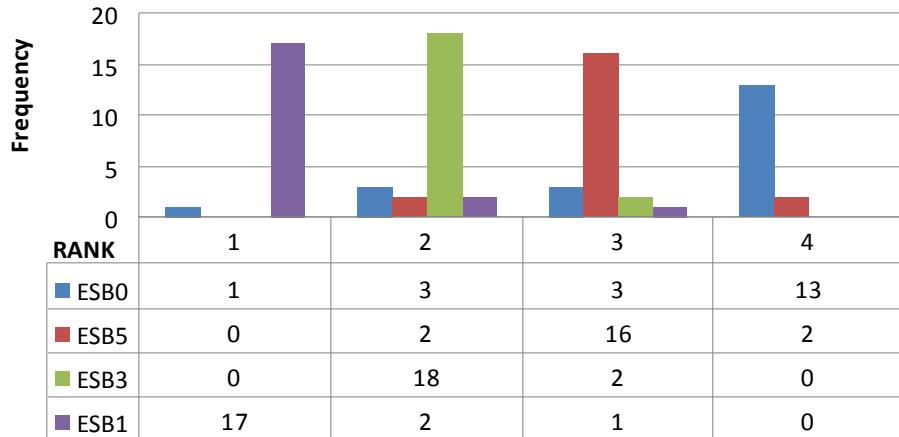
Figure 9:   Frequency of ranks using high-risk inventory buffer sizes based on PartShort

Frequency of ranks using no-risk inventory buffer sizes based on PackUp Effectiveness

RANK	1	2	3	4
ESB0	15	5	0	0
ESB5	1	7	6	6
ESB3	1	10	9	0
ESB1	9	10	0	1
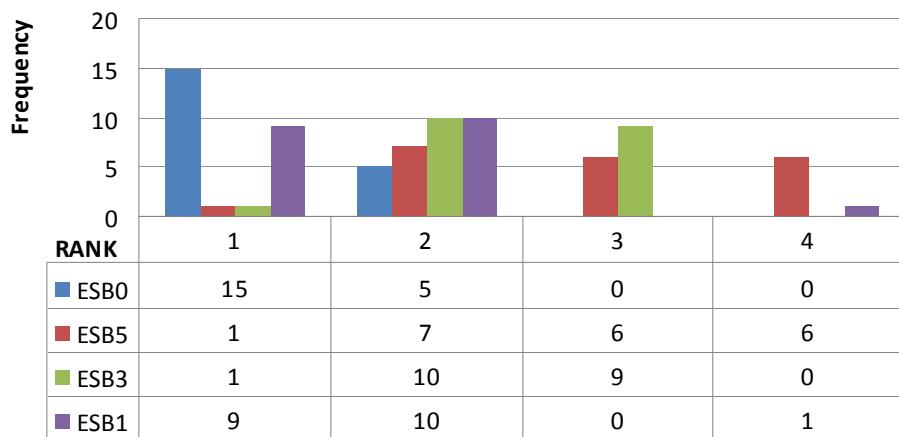
Figure 10:   Frequency of ranks using no-risk inventory buffer sizes based on PackUp Effectiveness

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Frequency of ranks using low-risk inventory buffer sizes based on PackUp Effectiveness

RANK	1	2	3	4
ESB0	18	1	0	1
ESB5	2	9	6	3
ESB3	2	10	8	0
ESB1	4	13	1	2

Figure 11:   Frequency of ranks using low-risk inventory buffer sizes based on PackUp Effectiveness

Frequency of ranks using medium-risk inventory buffer sizes based on PackUp Effectiveness

RANK	1	2	3	4
ESB0	20	0	0	0
ESB5	1	14	2	3
ESB3	1	15	4	0
ESB1	1	18	0	1
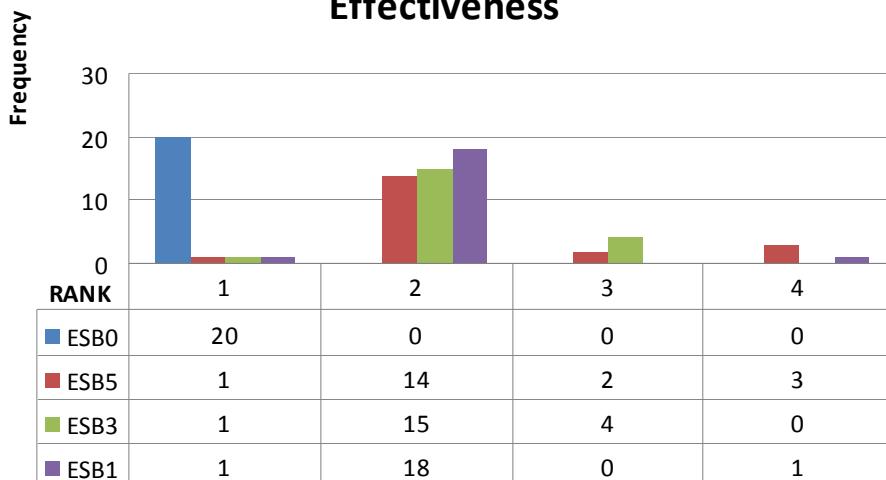
Figure 12:   Frequency of ranks using medium-risk inventory buffer sizes based on PackUp Effectiveness

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Frequency of ranks using high-risk inventory buffer sizes based on PackUp Effectiveness

RANK	1	2	3	4
ESB0	20	0	0	0
ESB5	3	11	4	2
ESB3	3	12	4	1
ESB1	3	16	1	0
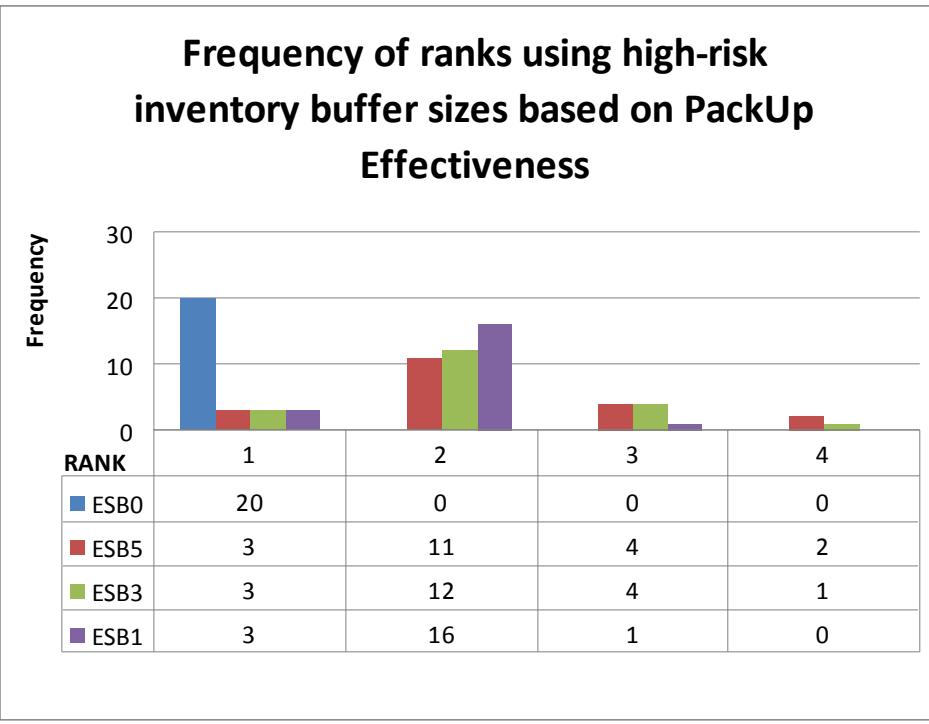
Figure 13:   Frequency of ranks using high-risk inventory buffer sizes based on PackUp Effectiveness

B.   THE IMPACT OF SELECTING A RISK LEVEL

The risk level selected to size inventory buffers has a significant impact on many desirable network properties such as attainability, flexibility, survivability and efficiency. Planners of the OPLOG system may prioritize a high level of attainability, defined in Chapter II as a node's ability to independently satisfy demand, and choose no-risk buffer sizing to achieve 100% PackUp Effectiveness at each node. Alternatively, planners may give high priority to flexibility, defined in Chapter II as a system's ability to quickly and effectively respond to changes in a system. Using no-risk inventory buffer sizing may lead to a loss of flexibility. By increasing the number of spare parts placed at each node, the system may lose the ability to quickly move to another location. Additionally, using no-risk buffer sizing may require more parts in the network than the support system has available thereby limiting the number of nodes that are allocated inventory buffers. If improving flexibility is given a high priority, assigning inventory buffers using low-, medium- or high-risk may be appropriate. Another important network property is

survivability defined in Chapter II as a node's vulnerability to enemy's hostile action (Kress 2002, 66). Placing logistical support at demand nodes, which are typically hostile environments, may decrease survivability. Operational planners may prioritize efficiency—defined as the ratio between inputs invested in logistics capability and estimated operational effectiveness. Each risk level represents a certain level of input of spare parts to the system. The ITN simulation model produces expected operational effectiveness for these varying levels of input. Together, these parameters serve as a proxy for determining efficiency.

In this section we first examine the estimated MOEs produced by the ITN model for each network configuration using inventory buffers, corresponding to the various risk levels, as determined by ELAT. Then we re-allocate the number of spare parts at each node and examine the resulting estimated MOEs.

Allocation of spare parts involves two decisions concerning range and depth. The range refers to the number of line items of spare parts included in the logistical support package. The depth refers to the quantity of each spare part included in the logistical support package. Applying no-risk buffer sizing, the range of parts allocated to forward nodes would include all parts that were ordered at least once during the time frame of the observed demand data. This could significantly increase the range of parts at the demand nodes thereby increasing the footprint of those nodes. Using the low risk buffer sizing method described in Chapter I, only parts that have been ordered in at least 3% of the time periods considered will be added to the range of line items. Using higher risk levels to determine inventory buffers will increase the percentage of time periods a part will need to have been ordered during the time frame considered to be added to the support package of each node. Using low-, medium- or high-risk level inventory buffer sizing may exclude many parts from the demand nodes and lead to some loss of operational effectiveness.

Selecting the risk level to use to determine inventory buffers for low-demand parts has a significant effect on the range of spare parts and the expected operational effectiveness. The range of spare parts dedicated to the OPLOG system should be determined considering the aggregated performance of the network. For example, Table

5 depicts that using ESB3 and low-risk inventory buffers removes all parts but 1 at the ESB. Though 6 nodes do not have parts allocated to their inventory buffer, their aggregated demand determines that 1 part is allocated to the ESB. Therefore, this low-demand part is included in the range of the network even though it is not included in the range of each node.

Table 4 depicts no-risk inventory buffer sizing for a low-demand aircraft part that requires 8 total parts in the network for every node to achieve 100% PackUp Effectiveness and 0 PartShort using ESB0. All other configurations require 9 total parts in the network to achieve 100% PackUp Effectiveness and 0 PartShort. Tables 5, 6 and 7 depict the distribution of spare parts and resulting measures of effectiveness using low-, medium- and high-risk level inventory buffer sizing. Using ESB3, no-risk buffer sizing allocates spare parts to every node in the network, but low-risk buffer sizing removes all spare parts but one at the ESB. Low-risk buffer sizing, using ESB3, reduces the total parts needed to support the network from 9 to 1, but also reduces PackUp Effectiveness from 100% to 0% and increases PartShort from 0 to 44.

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
No Risk										
ESB0	1	1	1	1	2	2		8	100%	0
ESB5	1	1	1	1	1	2	2	9	100%	0
ESB3	1	1	1	1	1	2	2	9	100%	0
ESB1	1	1	1	1	1	2	2	9	100%	0

Table 4:   No-risk inventory buffers for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Low Risk										
ESB0	0	0	0	0	1	1		2	55%	24
ESB5	0	0	0	0	0	1	1	2	11%	32
ESB3	0	0	0	0	0	0	1	1	0%	44
ESB1	0	0	0	0	0	0	1	1	0%	26

Table 5:　　　Low-risk inventory buffers for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Medium Risk										
ESB0	0	0	0	0	1	1		2	55%	24
ESB5	0	0	0	0	0	0	1	1	0%	53
ESB3	0	0	0	0	0	0	1	1	0%	44
ESB1	0	0	0	0	0	0	1	1	0%	26

Table 6:　　　Medium-risk inventory buffers for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
High Risk										
ESB0	0	0	0	0	0	0		0	0%	100
ESB5	0	0	0	0	0	0	0	0	0%	97
ESB3	0	0	0	0	0	0	0	0	0%	102
ESB1	0	0	0	0	0	0	0	0	0%	98

Table 7:　　　High-risk inventory buffers for gearbox assembly representing low-demand part

The ITN model quantifies the increase in effectiveness that results from adding additional spare parts. Using ESB3, comparing Table 5 containing low-risk buffer sizes, and Table 8 containing an alternative allocation of spare parts, adding one spare part to

the network improves PackUp Effectiveness from 0% to 12% and reduces PartShort from 44 to 27. Using ESB3, comparing Table 5 and Table 9, adding two additional spare parts to the network improves PackUp Effectiveness from 0% to 24% and reduces PartShort from 44 to 10. Using ESB3, comparing Table 9 and Table 4, reducing the quantity of spare parts in the network from 9 to 3 decreases PackUp Effectiveness from 100% to 24% but only increases PartShort from 0 to 10. By quantifying expected MOEs, planners have the information necessary to make important decisions regarding allocation of spare parts for low-demand items.

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
ESB0	0	0	0	0	1	1		2	55%	24
ESB5	0	0	0	0	0	1	1	2	11%	32
ESB3	0	0	0	0	0	1	1	2	12%	27
ESB1	0	0	0	0	0	1	1	2	12%	17

Table 8: Alternative inventory buffers for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
ESB0	0	0	0	0	1	2		3	51%	20
ESB5	0	0	0	0	1	1	1	3	21%	11
ESB3	0	0	0	0	1	1	1	3	23%	10
ESB1	0	0	0	0	1	1	1	3	25%	9

Table 9: Alternative inventory buffers for gearbox assembly representing low-demand part

The risk level for high-demand parts has a significant effect on the depth of spare parts and the expected operational effectiveness. The ITN model quantifies that effect. Using the ITN model after determining inventory buffers in ELAT may help produce the allocation of spare parts with the highest MOEs.

Using no-risk inventory buffer sizing, depicted in Table 10, ESB3 requires 56 total parts in the network to achieve 100% PackUp Effectiveness. Using low-risk inventory buffer sizing, depicted in Table 11, ESB3 decreases the quantity of spare parts required to support the network from 56 to 26 but also decreases PackUp Effectiveness from 100% to 59% and increases PartShort from 0 to 102. Applying higher levels of risk to determine inventory buffers, depicted in Tables 12 and 13, further reduces the number of spare parts needed to support the network and decreases the expected effectiveness of the system.

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
No Risk										
ESB0	2	2	2	2	16	18		42	100%	0
ESB5	2	2	2	2	15	15	18	56	100%	0
ESB3	2	2	2	2	15	15	18	56	100%	0
ESB1	2	2	2	2	9	9	22	48	100%	0

Table 10: No-risk inventory buffers for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Low Risk										
ESB0	0	0	0	2	14	14		30	90%	113
ESB5	0	0	0	1	9	9	12	31	64%	75
ESB3	0	0	0	0	6	6	14	26	59%	102
ESB1	0	0	0	0	3	3	16	22	55%	114

Table 11: Low-risk inventory buffers for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Medium Risk										
ESB0	0	0	0	1	11	12		24	84%	161
ESB5	0	0	0	0	6	7	10	23	59%	134
ESB3	0	0	0	0	4	5	12	21	58%	150
ESB1	0	0	0	0	2	2	14	18	44%	172

Table 12:   Medium-risk inventory buffers for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
High Risk										
ESB0	0	0	0	0	7	9		16	74%	310
ESB5	0	0	0	0	4	4	8	16	45%	320
ESB3	0	0	0	0	3	3	10	16	43%	308
ESB1	0	0	0	0	0	0	12	12	0%	450

Table 13:   High-risk inventory buffers for gyroscope representing high-demand part

Comparing proposed low-risk inventory buffer sizes in Table 11 and an alternative allocation of spare parts that produce the highest MOEs using the ITN model in Table 14, ESB3 has less PartShort and equal PackUp Effectiveness using less total spare parts by removing parts from the ESB and adding parts to the buffer at the MOBs. Comparing proposed high-risk buffer sizes in Table 13 and an alternative allocation of spare parts that produce the highest MOEs using the ITN model in table 15, ESB5 experiences less PartShort with equal total spare parts by removing parts from the ESB and adding parts to the buffer at the MOBs. Though inventory buffer sizing based on risk level is useful for allocating spare parts to a single node, network efficiency may be improved using the results from the ITN model.

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
ESB0	1	1	1	1	10	10		24	87%	134
ESB5	0	0	0	0	8	8	8	24	62%	93
ESB3	0	0	0	0	8	8	8	24	60%	91
ESB1	0	0	0	0	6	6	12	24	63%	81

Table 14:   Alternative inventory buffers for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
ESB0	0	0	0	0	7	9		16	74%	310
ESB5	0	0	0	0	5	5	6	16	49%	290
ESB3	0	0	0	0	5	5	6	16	48%	216
ESB1	0	0	0	0	4	4	8	16	53%	186

Table 15:   Alternative inventory buffers for gyroscope representing high-demand part

The ITN model produces estimated MOEs that can assist planners select the risk level in ELAT that allocates the appropriate level of parts input to the system to achieve the desired effectiveness. Additionally, once total inventory buffers are determined, the ITN model can help planners re-allocate parts within the network to improve estimated MOEs.

C.   NETWORK DESIGN USING NO-RISK BUFFER SIZING

In the previous section we established that selecting the appropriate risk level to use when developing inventory buffers is dependent on prioritizing desirable network properties. Similarly, selecting the design of the network—the number and placement of nodes—requires careful consideration of many network properties. The ITN model quantifies the impact of network design on achieving efficiency.

In this section, we rank the four network configurations using no-risk inventory buffers consistent with the method used in ELAT. Since no-risk inventory buffers produce 100% PackUp Effectiveness and 0 PartShort, we use the total spare parts dedicated to the system to compare the efficiency of each network configuration. Next, we distinguish rankings between low- and high-demand parts to analyze if the results are consistent for both demand patterns. Then, we present example results of a low-demand part and a high-demand part.

The Borda Method of Marks is used to aggregate the performance evaluations of the 20 selected spare parts, using the four network configurations, to facilitate comparison (Cook 1992, 134). For each part and MOE, the four network configurations are ranked. For example, the configuration that produces the highest PackUp Effectiveness is assigned a "1", the configuration that produces the next highest PackUp Effectiveness is assigned a "2", etc. The same method is used for PartShort. The configuration that has the fewest PartShort is assigned a "1" and the configuration that has the most PartShort is assigned a "4". The midpoint of ranks is used for ties. Ranks for each part are added together and divided by the number of parts analyzed to present an overall rank for each configuration. Rankings for low-demand and high-demand parts are separated to evaluate whether results differ based on frequency of demand.

Overall, using no-risk buffer sizing, ESB0 requires the least number of spare parts to achieve 100% PackUp Effectiveness and 0 PartShort. Comparing configurations with an ESB, the network generally requires less spare parts as the TRR decreases between the ESB and the demand nodes. 11 parts require the least total spare parts using ESB0, 5 require the least spare parts using ESB1 and 4 require an equal number of spare parts using ESB0 and ESB1. In all cases, ESB0 requires less spare parts than ESB5 and ESB3 to achieve 100% PackUp Effectiveness and 0 PartShort.
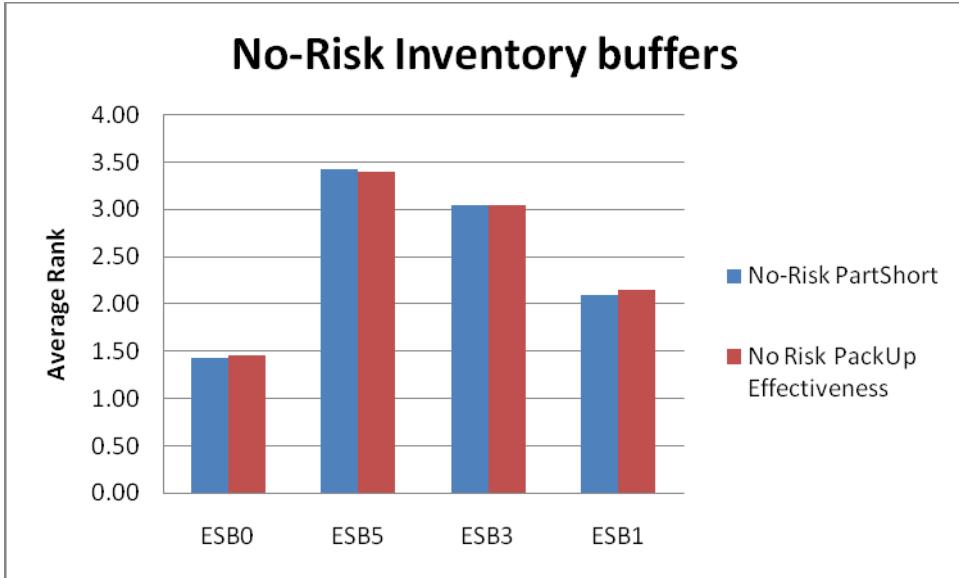
Figure 14:   Overall average ranks for no-risk inventory buffers sizes based on
network configuration

PartShort	
OVERALL	No Risk
ESB0	1.43
ESB5	3.43
ESB3	3.05
ESB1	2.1

PackUp Effect	
OVERALL	No Risk
ESB0	1.45
ESB5	3.4
ESB3	3.05
ESB1	2.15

Table 16:   Overall average ranks for each configuration. 20 spare parts were
analyzed using results from the ITN model for no-risk inventory buffers. ESB0
is the most efficient configuration, followed by ESB1 then ESB3 then ESB5.

Parts with high demand and parts with low demand have similar results. Using
no-risk inventory buffers, ESB0 is generally more efficient than the other configurations
with an ESB. Comparing the configurations with an ESB, results improve for high-
demand parts, depicted in Table 17, as the TRR decreases between the ESB and the
MOBs. However, results have less or no improvement for parts with low demand,
depicted in Table 18, as the TRR decreases between the ESB and the MOBs. Parts with
low demand generally require equal spare parts at each node to achieve approximately
equal MOEs no matter where the ESB is placed.

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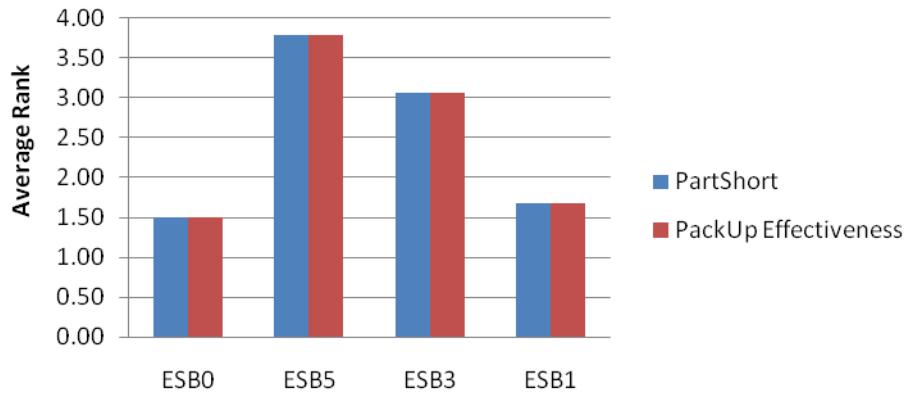
Figure 15:   Average ranks for no-risk inventory buffers based on high-demand
parts

PartShort		Packup Effect	
HIGH DEM	No Risk	HIGH DEM	No Risk
ESB0	1.50	ESB0	1.50
ESB5	3.78	ESB5	3.78
ESB3	3.06	ESB3	3.06
ESB1	1.67	ESB1	1.67

Table 17:   Average ranks of each configuration for parts with high demand.
20 spare parts were analyzed using results from the ITN model for no-risk
inventory buffers. ESB0 is the most efficient configuration, followed by ESB1
then ESB3 then ESB5.
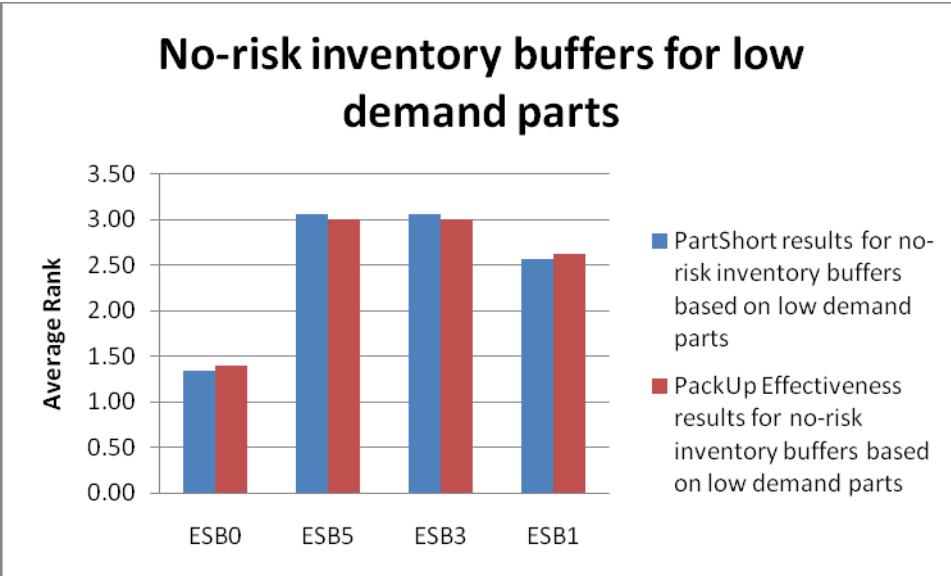
Figure 16:   Average ranks for no-risk inventory buffers based on low-demand parts

PartShort	
LOW DEM	No Risk
ESB0	1.33
ESB5	3.06
ESB3	3.06
ESB1	2.56

PackUp Effect	
LOW DEM	No Risk
ESB0	1.39
ESB5	3
ESB3	3
ESB1	2.61

Table 18:   Average ranks of each configuration for parts with low demand. 20 spare parts were analyzed using results from the ITN model for no-risk inventory buffers. ESB0 is the most efficient configuration, followed by ESB1 then ESB3 then ESB5.

Results for the CH-53 gyroscope, representing high demand at the MOB and moderate demand at the FOB, are shown in Table 19. It contains no-risk inventory buffers at each node for each configuration. ESB0 requires the least parts, 42, in the network to achieve 100% effectiveness. ESB1 requires the next least total parts, 48, and significantly fewer parts at the MOBs to obtain maximum effectiveness. ESB5 and ESB3 also require fewer parts at the MOBs than ESB0 but require more total parts supporting the network, 56, to obtain 100% effectiveness.

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
No Risk										
ESB0	2	2	2	2	16	18		42	100%	0
ESB5	2	2	2	2	15	15	18	56	100%	0
ESB3	2	2	2	2	15	15	18	56	100%	0
ESB1	2	2	2	2	9	9	22	48	100%	0

Table 19:   No-risk inventory buffer for gyroscope representing high-demand part

The gearbox assembly, representing low demand at both the MOB and FOB, is shown in Table 20. It contains the no-risk inventory buffers at each node for each configuration. ESB0 requires the least quantity of spare parts in the network using no-risk buffer sizing. All other configurations require the same total number of spare parts to achieve 100% effectiveness.

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
No Risk										
ESB0	1	1	1	1	2	2		8	100%	0
ESB5	1	1	1	1	1	2	2	9	100%	0
ESB3	1	1	1	1	1	2	2	9	100%	0
ESB1	1	1	1	1	1	2	2	9	100%	0

Table 20:   No-risk inventory buffer for gearbox assembly representing low-demand part

D.   NETWORK DESIGN USING BUFFER SIZING WITH RISK

In this section, we present rankings to compare the efficiency of the four network configurations using low-, medium- and high-risk levels to determine inventory buffers. Spare parts at each node have been re-allocated from the number suggested by ELAT to use a common denominator of total spare parts in the network to compare alternative configurations in a proper way. The four inventory buffer sizing risk levels are used as a basis to determine total spare parts to dedicate to the system for each configuration. However, spare parts are re-allocated to find the inventory buffer sizes that produce the

highest values of the selected MOEs using the ITN simulation model. The rankings of low-demand parts and high-demand parts are separated to analyze if the results are consistent for both demand patterns. Then, we present example results of a low-demand part and a high-demand part.

Planners must prioritize between the two MOEs—PackUp Effectiveness and PartShort—before designing the network using low-, medium- or high-risk inventory buffers. The two MOEs do not improve in tandem as a result of changing the design of the support network. A system that increases the percentage of demands satisfied on the day demanded does not necessarily improve the response time for unsatisfied demand. There is no configuration that provides the highest PackUp Effectiveness with fewest PartShort requiring the least spare parts.

Table 21 displays overall results for PartShort using low-, medium-, and high-risk buffer sizes. ESB3 and ESB1 have fewer PartShort than ESB0 and ESB5 with equal total spare parts in the network. Approximately equal quantities of parts have fewer PartShort using ESB0 and ESB5. Increasing TRR between the ESB and the demand nodes increases PartShort. Results are consistent between low-, medium- and high-risk inventory buffers.
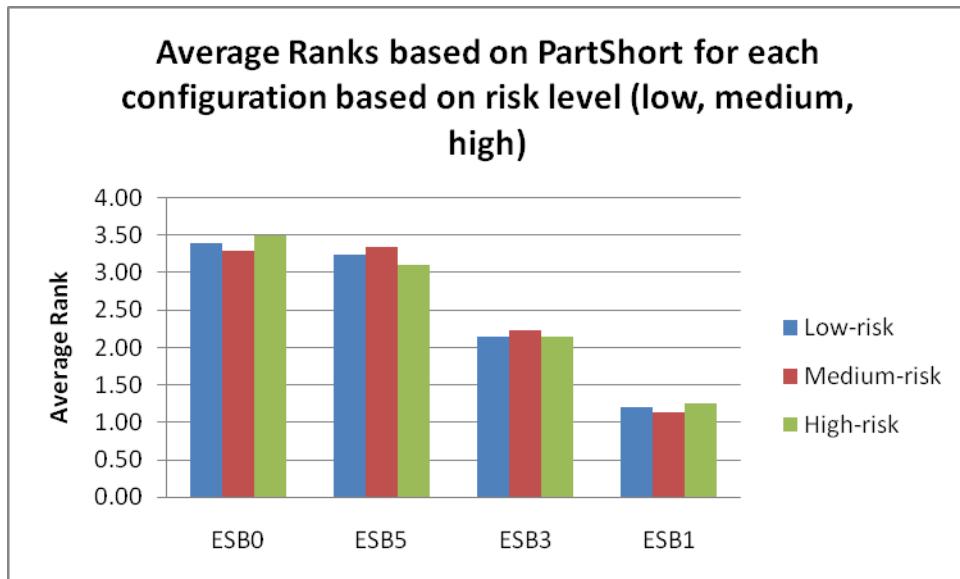

Figure 17:   Average ranks for each network configuration based on risk (low, medium, high)

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PartShort			
OVERALL	Low Risk	Med Risk	High Risk
ESB0	3.40	3.30	3.50
ESB5	3.25	3.35	3.10
ESB3	2.15	2.23	2.15
ESB1	1.20	1.13	1.25

Table 21:   Overall average ranks based on PartShort for low-, medium- and high-risk inventory buffers

Table 22 displays overall results for PackUp Effectiveness using low-, medium-, and high-risk buffer sizes. ESB0 has higher PackUp Effectiveness than the other configurations for all risk levels.   These results reflect that—using a common denominator of total spare parts dedicated to the logistical support network—placing parts at the ESB requires removing parts from the demand nodes thereby having fewer parts available on the day ordered. Once the ESB is added to the network, there is not a significant difference between configurations based on the distance between the ESB and the demand nodes. Using low-risk buffer sizing, ESB1 has higher PackUp Effectiveness than ESB5 and ESB3 for 7 out of 20 parts analyzed while 9 parts have approximately equal PackUp Effectiveness. Using medium-risk buffer sizing, ESB1 has higher PackUp Effectiveness than ESB5 and ESB3 for 4 out of 20 parts analyzed while 15 parts have approximately equal PackUp Effectiveness.   Using high-risk buffer sizing, ESB1 experiences higher PackUp Effectiveness than ESB5 and ESB3 for 4 out of 20 parts analyzed while 13 parts have approximately equal PackUp Effectiveness.
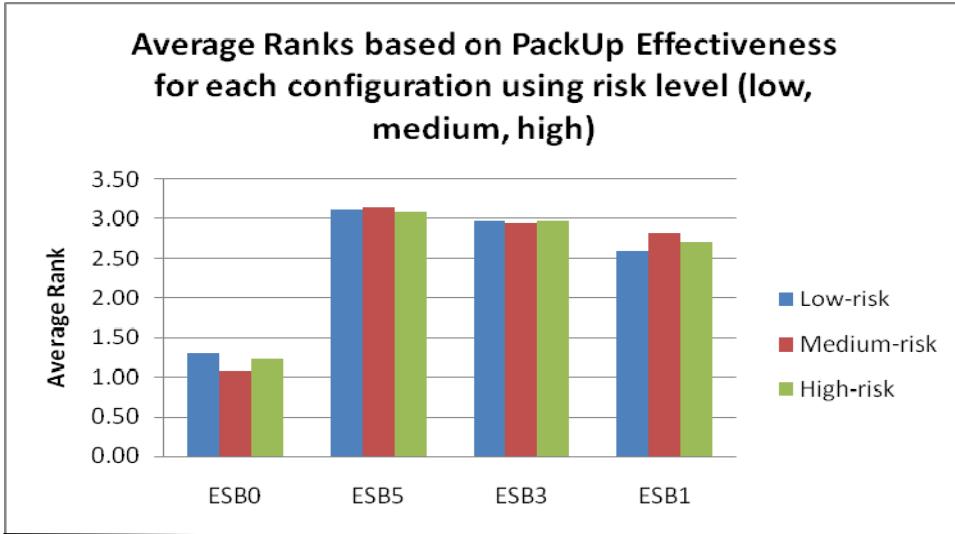
Figure 18:   Average ranks based on PackUp Effectiveness for each
configuration using risk level (low, medium, high)

PackUp Effect			
OVERALL	Low	Med	High
ESB0	1.30	1.08	1.23
ESB5	3.13	3.15	3.10
ESB3	2.98	2.95	2.98
ESB1	2.60	2.83	2.70

Table 22:   Overall average ranks based on PackUp Effectiveness for low-,
medium- and high-risk inventory buffers

Results, depicted in Table 23, were consistent between parts with low demand and parts with high demand. ESB3 and ESB1 have fewer PartShort than ESB0 and ESB5 for both high-demand and low-demand parts. ESB0 and ESB5 have mixed results compared with each other. High-demand parts perform better using ESB5 while low-demand parts perform better using ESB0. Using low risk, 4 low-demand parts have fewer PartShort using ESB0 than ESB5, 3 low-demand parts have fewer PartShort using ESB5 than ESB0, and 2 low-demand parts have approximately equal shortages using both ESB5 and ESB0. Using low-risk buffer sizing, 6 high-demand parts have fewer PartShort using ESB0 than ESB5 while 3 high-demand parts have fewer PartShort using ESB5 than ESB0.

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Figure 19:   Average ranks based on PartShort using risk level (low, medium, high) based for high-demand parts


Figure 20:   Average ranks based on PartShort using risk level (low, medium, high) based for low-demand part

PartShort					PartShort			
HIGH DEM	Low Risk	Med Risk	High Risk		LOW DEM	Low Risk	Med Risk	High Risk
ESB0	3.61	3.61	3.89		ESB0	3.17	2.94	3.22
ESB5	3.22	3.17	3.11		ESB5	3.22	3.50	3.00
ESB3	2.06	2.11	2.00		ESB3	2.28	2.39	2.22
ESB1	1.11	1.11	1.00		ESB1	1.33	1.17	1.56

Table 23:   Average ranks, isolated for high- and low-demand parts, based on PartShort using low-, medium- and high-risk inventory buffers

Table 24 depicts results based on PackUp Effectiveness for high-demand parts and low-demand parts in isolation. ESB0 produces higher PackUp Effectiveness than the other configurations, regardless of demand pattern, using low-, medium- and high-demand inventory buffers. If the ESB is included in the network, parts with high demand experience higher PackUp Effectiveness with shorter TRR between the ESB and the demand nodes. However, parts with low demand experience approximately equal PackUp Effectiveness regardless of the TRR between the ESB and the demand nodes.
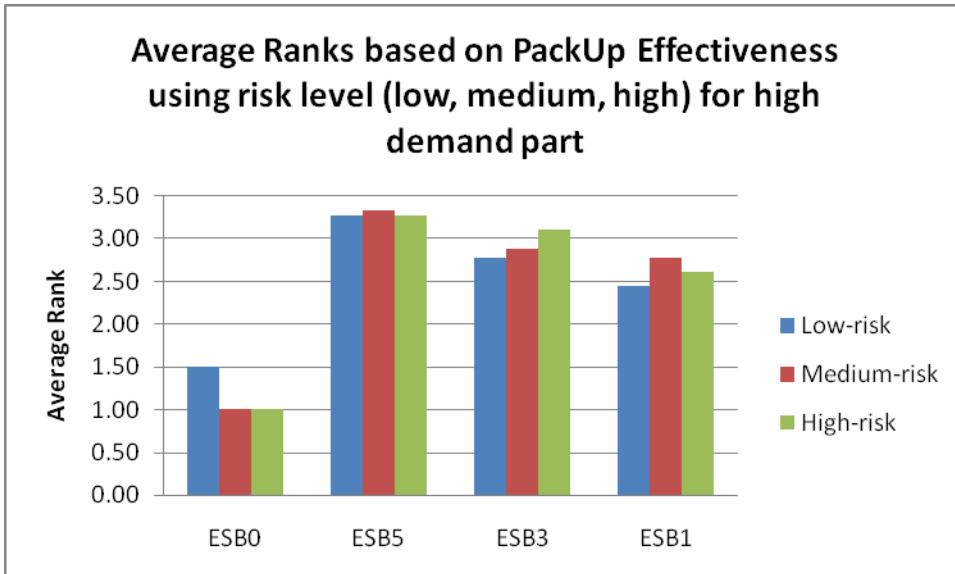
Figure 21:   Average ranks based on PackUp Effectiveness using risk level (low, medium, high) for high-demand parts

Figure 22: Average ranks based on PackUp Effectivness using risk level (low, medium, high) for low-demand parts

PackUp Effect			
HIGH DEM	Low Risk	Med Risk	High Risk
ESB0	1.50	1.00	1.00
ESB5	3.28	3.33	3.28
ESB3	2.78	2.89	3.11
ESB1	2.44	2.78	2.61

PackUp Effect			
LOW DEM	Low Risk	Med Risk	High Risk
ESB0	1.17	1.17	1.50
ESB5	2.89	2.94	2.83
ESB3	3.06	2.94	2.83
ESB1	2.89	2.94	2.83

Table 24: Average ranks, isolated for high- and low-demand parts, based on PackUp Effectiveness using low-, medium- and high-risk inventory buffers

Tables 25, 26 and 27 contain results for the gyroscope representing a high-demand part. Using equivalent total buffers for the system, configurations with an ESB—ESB5, ESB3 and ESB1—result in fewer PartShort than ESB0; however ESB0 produces higher PackUp Effectiveness than the other configurations.

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Low Risk										
ESB0	1	1	1	1	14	14		32	93%	73
ESB5	1	1	1	1	9	9	10	32	82%	42
ESB3	1	1	1	1	9	9	10	32	85%	36
ESB1	1	1	1	1	9	9	10	32	83%	34

Table 25:   Low-risk buffer sizing for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Medium Risk										
ESB0	1	1	1	1	10	10		24	87%	134
ESB5	0	0	0	0	8	8	8	24	62%	93
ESB3	0	0	0	0	8	8	8	24	60%	91
ESB1	0	0	0	0	6	6	12	24	63%	81

Table 26:   Medium-risk buffer sizing for gyroscope representing high-demand part

010632830	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
High Risk										
ESB0	0	0	0	0	7	9		16	74%	310
ESB5	0	0	0	0	5	5	6	16	49%	290
ESB3	0	0	0	0	5	5	6	16	48%	216
ESB1	0	0	0	0	4	4	8	16	53%	186

Table 27:   High-risk buffer sizing for gyroscope representing high-demand part

Tables 28, 29 and 30 contain results for the gearbox representing a low-demand part. It experiences approximately equal PartShort using ESB5, ESB3 and ESB1. ESB0 experiences approximately twice as many PartShort as the other three configurations.

However, ESB0 has significantly higher PackUp Effectiveness than the other three configurations. ESB5, ESB3 and ESB1 have approximately equal PackUp Effectiveness for each risk level.

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Low Risk										
ESB0	0	0	0	0	1	2		3	51%	20
ESB5	0	0	0	0	1	1	1	3	21%	11
ESB3	0	0	0	0	1	1	1	3	23%	10
ESB1	0	0	0	0	1	1	1	3	25%	9

Table 28:   Low-risk buffer sizing for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
Med Risk										
ESB0	0	0	0	0	1	1		2	55%	24
ESB5	0	0	0	0	0	1	1	2	11%	32
ESB3	0	0	0	0	0	1	1	2	12%	27
ESB1	0	0	0	0	0	1	1	2	12%	17

Table 29:   Medium-risk buffer sizing for gearbox assembly representing low-demand part

014117040	Fob1 Buffer	Fob2 Buffer	Fob3 Buffer	Fob4 Buffer	Mob1 Buffer	Mob2 Buffer	ESB Buffer	Total Buffer	PackUp Effect	PartShort
High Risk										
ESB0	0	0	0	0	0	1		1	28%	112
ESB5	0	0	0	0	0	0	1	1	0%	53
ESB3	0	0	0	0	0	0	1	1	0%	44
ESB1	0	0	0	0	0	0	1	1	0%	26

Table 30:   High-risk buffer sizing for gearbox assembly representing low-demand part

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V. CONCLUSIONS

A. THESIS OBJECTIVES

This thesis is aimed at assisting Marine Corps aviation logistical planners to efficiently design the support network and allocate resources for deployed operations. It develops an inter-temporal network (ITN) simulation model that measures the operational effectiveness of four network configurations with respect to four inventory buffer sizes obtained using the same methodology as ELAT. The buffer sizes correspond to four risk levels—no, low, medium and high. Two MOEs are used: PackUp Effectiveness, which represents the percentage of demands satisfied on the day demanded and PartShort, which represents the magnitude and duration of unsatisfied demands during a given period.

B. EVALUATING ALTERNATIVE NETWORK CONFIGURATIONS AND ALLOCATING SPARE PARTS

The main takeaways from this research are:

(1) Operational planners must prioritize desirable network properties. There are no dominating network configurations for all risk levels with respect to the selected MOEs.

(2) If the objective is a high level of attainability at each node—measured by 100% PackUp Effectiveness and 0 PartShort—then no-risk inventory buffer sizing is required. No-risk inventory buffers will have a significantly greater range and depth than other risk level inventory buffers. For no-risk inventory buffer sizes, ESB0 dominates all other alternative network configurations.

(3) If operational flexibility or survivability, which seek smaller logistical footprint at the demand nodes, is a high priority, planners should be willing to accept less than maximum effectiveness to reduce the logistical support footprint at each node. In this situation, low-, medium- or high-risk level buffer sizing are appropriate.

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(4) Using low-, medium- or high-risk buffer sizing levels, planners must prioritize MOEs before designing the support network. PackUp Effectiveness and PartShort do not necessarily improve in tandem as a result of changing the design of the support network. A system that increases the percentage of demands satisfied on the day demanded does not necessarily improve the response time for unsatisfied demand. Considering each one of these two MOEs may result in different network configurations.

(5) For all non-zero risk levels, if the objective is to maximize PackUp Effectiveness, ESB0 is the dominating alternative.

(6) For all non-zero risk levels, if the objective is to minimize PartShort, ESB1 is the dominating alternative. Also, any network with an ESB less than five days TRR from the demand nodes will outperform ESB0.

(7) If the ESB is included, performance improves as the TRR between the ESB and the demand nodes is minimized.

C.   FUTURE EXTENSIONS

1.   In this study we used a single value to estimate the TRR between nodes because TRR data is unavailable. In reality, TRR is a random variable that may be subject to significant variance. Once data is collected and becomes available, the TRR should be incorporated in the model along its estimated probability distribution.

2.   The model presented in this thesis was limited to spare parts. It can be extended to include other resources such as transportation, repair capability, mobile facilities, and manpower.

3.   The model used in this thesis considers spare parts individually. It can be extended to consider demands for multiple parts and model their interactions.

4.   The original ITN model is an optimization model. The model used in this thesis can be extended to produce the optimal allocation of spare parts that produce objective functions that maximize selected MOEs while meeting constraints on the total number of spare parts dedicated to the logistics support network.

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